Aspects of the Circulation on the Newfoundland Continental Shelf

Brian Petrie

Atlantic Oceanographic Laboratory
Ocean Science and Surveys, Atlantic
Department of Fisheries and Oceans

Bedford Institute of Oceanography
P.O. Box 1006
Dartmouth, Nova Scotia B2Y 4A2

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Les rapports techniques peuvent être considérés comme des publications à part entière. Le titre exact figure au-dessus du résumé du chaque rapport. Les résumés des rapports seront publiés dans la revue Résumés des sciences aquatiques et halieutiques et les titres figureront dans l'index annuel des publications scientifiques et techniques du Ministère.

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Les établissements des Sciences et Levés océaniques dans les régions et à l'administration centrale ont cessé de publier leurs diverses séries de rapports depuis décembre 1981. Vous trouverez dans l'index des publications du volume 38 du *Journal canadien des sciences halieutiques et aquatiques*, la liste de ces publications ainsi que le dernier numéro paru dans chaque catégorie. La nouvelle série a commencé avec la publication du Rapport n° 1 en janvier 1982.

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Dartmouth, Nova Scotia
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ABSTRACT

Petrie, B. 1982. Aspects of the circulation on the Newfoundland Continental Shelf. Can. Tech. Rep. Hydrogr. Ocean Sci. 11 : 78 p.

This report presents two documents dealing with various aspects of the circulation on the Newfoundland Continental Shelf. The first document considers residual (non-tidal) currents in the Hibernia area presenting basic statistics of about one year of current data from the site and a discussion of wind forcing, data quality, simple forced models of the current, and likely extreme currents. The second document confines itself to a discussion of tidal currents and elevations at the Hibernia (46° 45'N, 48° 50'W) site.

RESUME

Petrie, B. 1982. Aspects of the circulation on the Newfoundland Continental Shelf. Can. Tech. Rep. Hydrogr. Ocean Sci. 11 : 78 p.

On présente ici deux rapports discutant plusieurs aspects de la circulation sur le plateau continental de Terre-Neuve. Le premier considère les courants résiduels près d'Hibernia: on présente à peu près un an de données sur les courants et on discute l'influence du vent, la qualité des données, des modèles simples du courant, et aussi les courants extrèmes qui pourraient exister. Le deuxième rapport se limite à une discussion des courants de mareés et des élévations à la site Hibernia (46° 45'N, 48° 50'O).

INTRODUCTION

This report has been put together to satisfy certain requirements the Resource Management Branch (RMB), Department of Energy, Mines and Resources had concerning the physical oceanography of the Newfoundland Continental Shelf and the Hibernia area in particular. The RMB defined their needs as follows:

(a) general overview of the oceanographic conditions in the area;

(b) analysis of the spatial and temporal variability of the ocean current profiles in the area. This variability should also be assessed in terms of the major forcing functions;

(c) determination from the available current meter records of the per cent exceedance of speed and associated confidence limits of the surface, mid-water depth and bottom;

(d) (estimation by the most appropriate means of the long-term (1-year, 10-year, 50-year and 100-year) current speed and direction and associated confidence limits for the three depths indicated in c); and,

(e) estimation of the average and maximum tidal range, their associated confidence limits and the likely long-term extremes.

The research required above is to be carried out using historical data, available literature, and the recent observations by Mobil's consultants and the federal government. In addition the development of a simple box model that relies on temperature, salinity and density variations as well as measured currents will be needed.

Three documents addressing these requirements have been completed. The first, dealing with the general circulation on the Newfoundland Shelf,

was sent to the RMB in January. Since that time it has been revised (with Carl Anderson) in preparation for submission to an oceanographic journal. Two other documents dealing with tidal and residual flows are presented here. A distinct advantage of the Fisheries and Oceans Report Series is that it allows flexibility of presentation. That flexibility is severely tested in this document.

ACKNOWLEDGEMENTS

A large portion of the data analyses for this report was done by Marion Schutzenmeier who in the course of her work overcame many difficulties with data formats, instrument logs (or lack of same), and untried programs. Wayne Richard promptly and skillfully doctored new programs and modified existing ones to perform tasks they weren't originally designed to do. Useful comments were provided by John Lazier, Charles Ross, Stuart Smith and Daniel Wright. The Resource Management Branch of the Department of Energy, Mines and Resources provided some funding, which accelerated the pace of this work, and exhibited patience as deadlines were passed without a completed manuscript. Finally, Mobil Oil Canada, Ltd., allowed us early access to their current meter data taken at the Hibernia site.

RESIDUAL CURRENTS AT THE HIBERNIA SITE

This document has been prepared for the Resource Management Branch of the Department of Energy, Mines and Resources

by

Brian Petrie

Atlantic Oceanographic Laboratory

Bedford Institute of Oceanography

Dartmouth, Nova Scotia

B2Y 4A2

1. INTRODUCTION

This document presents an analysis of current meter data from the Hibernia site. The emphasis is placed on residual (non-tidal) currents, the tidal flows having been dealt with in another document. To quote a reviewer, "The first half gives a rather plodding routine analysis ... but it "gets better and better as it goes on." I think the plodding analysis is required so please bear with it. Percent distribution of current speed and direction will be given (Section 2) for 4 depths designated surface, mid-depth, near bottom and bottom, the latter being 1/2 m off the bottom on a specially constructed mooring. Next, spectra of the currents will be presented followed by (Section 4) a breakdown of variance into tidal, inertial period and low frequency bands. Low frequency current records from the same mooring were merged and subjected to empirical orthogonal function analysis (Section 5). The structure of the currents containing the most variance and the behaviour of these modes with time will be shown. The spectra of the wind field will then be presented (Section 6) followed by a discussion of wave effects (Section 7) on the quality of current data. Some comparisons of a simple model of currents forced by wind will be shown (Section 8). Finally, a discussion of extreme currents and other topical issues will be presented.

2. DISTRIBUTION OF CURRENT SPEED AND DIRECTION

The statistics (with tides removed) of current speed (Table 1) and direction (Table 2) are given as cumulative percentage and percent exceedance for 5 cm/s bands and percentage distribution for 20° bands. The results are based on the data records listed in Table 3. Distributions were derived for 4 levels, namely, near surface (within surface mixed

TABLE 1. Statistics of Current Speed

(A) Near-Surface

(B) Mid-Depth

Speed Range (cm/s)	Cumulative Percentage	Percent Exceedance	Cumulative Percentage	Percent Exceedance
0-5	3.00	97.00	8.65	91.35
5-10	13.13	86.87	30.88	69.12
10-15	29.33	71.67	54.63	45.37
15-20	48.61	51.39	72.88	27.12
20-25	65.91	34.09	84.59	15.41
25-30	79.94	20.06	91.87	8.13
30-35	89.17	10.83	96.13	3.87
35-40	94.37	5.63	98.26	1.73
40-45	97.00	3.00	99.33	0.67
45-50	98.40	1.60	99.88	0.12
50-55	99.19	0.81		
55-60	99.53	0.47		
60-65	99.76	0.24		
65-70	99.94	0.06		

(C) Near Bottom

(D) Bottom

Speed Range (cm/s)	Cumulative Percentage	Percent Exceedance	Cumulative Percentage	Percent Exceedance
0-5	17.6	82.4	43.04	56.96
5-10	52.1	47.9	84.62	15.38
10-15	77.1	22.9	97.79	2.21
15-20	89.1	10.9	99.74	0.26
20-25	94.6	5.4	99.99	0.01
25-30	97.4	2.6		
30-35	98.9	1.1		
35-40	99.6	0.4		

TABLE 2. Percentage Distribution of Current Direction

Direction (°T)	Near Surface	Mid Depth	Near Bottom	Bottom
0–20	4.8	6.4	5.3	6.5
20–40	4.6	6.1	5.5	5.9
40–60	4.1	5.0	5.5	4.8
60–80	4.6	4.7	5.5	4.4
80–100	5.1	4.9	6.0	4.1
100–120	5.7	5.3	6.0	4.2
120–140	6.4	6.1	6.9	5.0
140–160	7.1	7.5	7.1	6.5
160–180	7.1	6.7	6.2	7.2
180–200	6.5	5.9	6.3	6.8
200–220	6.2	5.2	6.4	5.9
220–240	5.5	4.7	5.6	5.6
240–260	5.3	4.6	5.0	5.1
260–280	4.7	4.9	4.3	5.0
280–300	5.2	5.3	4.4	5.2
300–320	5.9	5.4	4.6	5.6
320–340	5.9	5.5	4.7	6.3
340–360	5.4	6.0	4.7	6.6

TABLE 3. Data used in Formulating Current Meter Statistics

	Season	Latitude (°N)	Longitude (°W)	Depth (m)	Start Time
(A) Near surface					
	Winter	46 45.0	48 49.5	31.5	29/01/1980
	Spring	46 44.5	48 49.6	15	13/05/1980
		46 34.0	48 21.0	25	13/05/1980
	Summer	46 44.5	48 49.6	15	19/06/1980
		46 34.4	48 21.2	25	19/06/1980
		46 34.4	48 21.2	25	24/07/1980
	Fall	46 47.0	48 46.0	25	02/10/1980
		47 7.0	47 57.5	35	02/10/1980
(B) Mid-Depth					
	Winter	46 44.3	48 53.2	45	07/12/1980
	Spring	46 44.5	48 49.6	30	13/05/1980
		46 34.0	48 21.0	50	13/05/1980
	Summer	46 44.5	48 49.6	30	19/06/1980
		46 34.4	48 21.2	50	19/06/1980
		46 34.4	48 21.2	50	24/07/1980
	Fall	46 47.0	48 46.0	45	02/10/1980
		47 7.0	47 57.5	95	02/10/1980
(C) Near Bottom					
	Spring	46 34.0	48 21.0	80	13/05/1980
	Summer	46 44.5	48 49.6	60	19/06/1980
		46 34.4	48 21.2	80	19/06/1980
		46 34.4	48 21.2	80	24/07/1980
	Fall	46 47.0	48 46.0	60	02/10/1980
		47 7.0	47 57.5	150	02/10/1980
(D) Bottom					
	Spring	46 44.5	48 49.6	75	19/04/1980
		46 34.4	48 21.2	97	19/04/1980
		46 44.5	48 49.6	97	19/04/1980
		46 44.5	48 49.6	74	04/06/1980
		46 44.0	48 49.0	74	04/06/1980
		46 34.4	48 21.2	74	04/06/1980

TABLE 3. Continued

Season	Latitude (°N)	Longitude (°W)	Depth (m)	Start Time
Summer	46 38.0	48 48.0	72	27/07/1980
	46 37.0	48 31.0	94	27/07/1980
	46 42.0	48 24.0	99	27/07/1980
Fall	46 37.1	47 43.5	116	07/12/1980
	46 46.5	48 5.0	121	07/12/1980
	46 37.5	48 16.0	105	07/12/1980
	46 37.5	47 45.0	131	07/12/1980
	46 37.5	49 0.0	72	07/12/1980

layer), mid-depth (in or below seasonal thermocline) near bottom (within 20 m of the bottom) and bottom (1/2 m off bottom). Seasonal averages were computed where possible before formulating an annual average.

One of the methods suggested for constructing estimates of long term (1 year, 10 year, 50 year, and 100 year) peak currents is based on techniques used for extreme wave forecasting. It consists of constructing a probability plot of current distribution versus speed. Lognormal probability plots were constructed for all depth levels using seasonally averaged data (Table 3). The results (Table 4) indicate that we would have little confidence in extending these distributions to make estimates of long term current statistics. In addition, the chi-square test is not sensitive to systematic deviations from lognormal - systematic differences were observed for all distributions. In all cases the data indicated a lower probability of occurence of high currents than the least squares fit. The best fit lognormal distributions have projected excessive current estimates (Table 4) for the long term. With the present data set this method is inadequate to predict long term extreme currents. However, in a later section other means of estimating extreme currents will be discussed.

3. CURRENT SPECTRA

Figures 1 to 5 show variance conserving plots of current meter spectra from different sites and times in the area of the Hibernia discovery. Where possible, successive time series from the same depth and location have been joined to give a longer data set resulting in improved spectral estimates and the possibility of resolving lower frequencies. The spectrum shown in Fig. 1 was computed from data which were recorded in

TABLE 4. Confidence levels for lognormal distributions of residual currents based on chi-square test. One hundred year maximum residual current is shown in cm/s.

Near surface (55%)	432	Mid-depth (75%)	402
Near bottom (80%)	344	Bottom (30%)	138

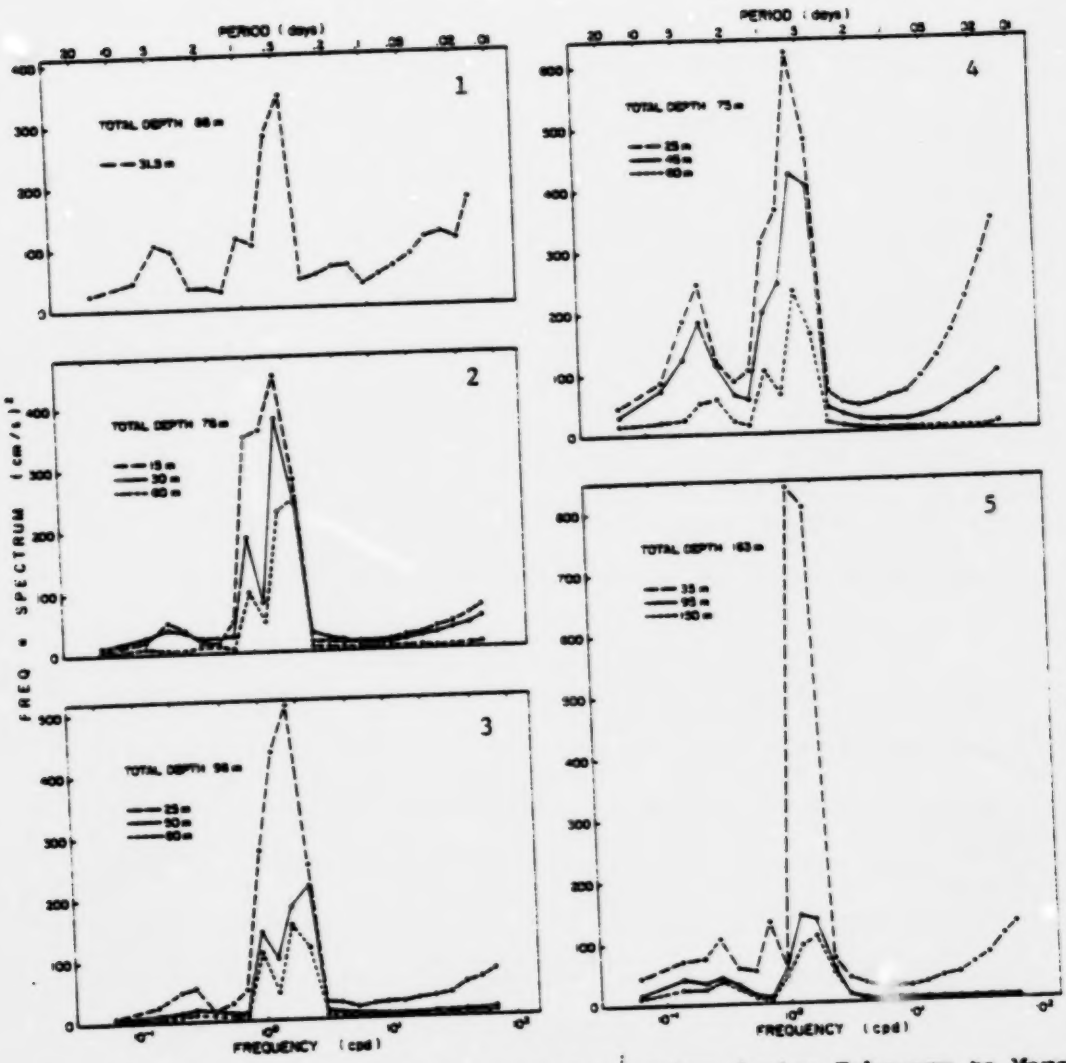


Fig. 1 Spectrum of current observations taken during February to March, 1980 at a depth of 31.5 m. Sedco 709 site.

Fig. 2 Spectra of current observations taken during May to July, 1980 at depths of 15, 30 and 60 m. Sedco 709 site.

Fig. 3 Spectra of current observations taken during May to August, 1980 at depths of 25, 50 and 80 m. Zapata Ugland site.

Fig. 4 Spectra of current observations taken during October to February, 1980 at depths of 25, 45 and 60 m. Sedco 706, Ocean Ranger site.

Fig. 5 Spectra of current observations taken during October to January, 1980 at depths of 35, 95 and 150 m. Zapata Ugland site.

February-March 1980. The other diagrams follow sequentially in time with Fig. 5 representing the period of October 1980 to January 1981. The main features of the spectra are the following:

(i) Major contribution to the total variance from the tidal and inertial band for all records.

(ii) Variation of energy with depth in the tidal-inertial band with generally higher levels near the surface.

(iii) Significant variance in the 2 to 10 d band which is larger in the winter and fall (Fig. 1 and 4) and at shallower depths. There also appears to be a difference which depends on the total water depth (compare Fig. 4 and 5).

(iv) A distinct tendency for spectral estimates to increase in the frequency band 10 to 100 cpd. This is most evident for the shallower records and those taken during fall and winter (see Fig. 4 in particular). A close examination of the records from the Sedco 706 and Ocean Ranger site for the period covered by Fig. 4 indicates that the rise in the spectra at high frequencies may be due to rapid variation of direction rather than spikes in the rate. E. Daddio (Evans-Hamilton, pers. comm.) was the first to point this out. Rapid variations in direction seem to occur during high wind and wave conditions. It is possible that the wave action may introduce a low frequency modulation to the rate since Savonius-type rotors are spun up in the presence of a wave field. In addition, the variation of energy with depth (Fig. 2-5) may be spurious. These features have been observed by Halpern and Pillsbury (1976).

4. CURRENT VARIANCE

The current variance has been considered as a function of season, depth and frequency for moorings placed in a water depth less than 100 m. The results are given in Table 5 for three depth ranges previously defined, as seasonal averages beginning with the winter of 1980 (February-March) and for inertial, tidal and low frequency bands. Estimates of variance for the inertial band were made using the spectral values from the Plansearch data reports. Tidal variance was computed from the difference between raw and residual (tides removed) records. Low frequency variance was calculated after a low pass filter (100% of power passed for periods longer than 1.8 d, 10% passed at a period of 1.1 d) had been applied to the data. Total and low frequency variance are highest in fall and winter and nearer the surface, in all probability associated with the annual cycle in winds. There is a distinct tendency for inertial period motions to be more energetic in spring and summer and at shallower depths.

It is of interest to compute the ratio of the rms amplitude for the varying currents to the mean current. The average of this ratio for all depths (excluding the instruments 1/2 m off the bottom) and for the total depth less than 100 m was 12.7. For moorings greater than 100 m but less than 200 m the ratio was 1.9. On the other hand Mountain (1980) reported that for an instrument moored at 110 m depth in the Labrador Current on the 490 m isobath the ratio was 0.2. On the shelf variability dominates the mean flow but as one moves offshore the mean currents become increasingly important.

TABLE 5. Seasonal Current Variance (cm^2/s^2) for three depth ranges.

	Total	Low Freqency	Tidal	Inertial
(A) Near-surface				
Winter	720	275	185	16
Spring	565	73	201	107
Summer	675	66	130	127
Fall	1043	363	203	60
Winter	1487	337	299	46
(B) Mid-depth				
Spring	342	51	175	34
Summer	292	36	122	53
Fall	645	265	173	24
Winter	794	245	270	26
(C) Near-bottom				
Spring	180	25	81	34
Summer	196	22	96	18
Fall	327	106	100	40
Winter	328	101	154	10

5. VERTICAL CURRENT STRUCTURE

The tidal currents discussed in a previous document specify the current structure in the frequency band 1 to 2 cpd with the exception of the inertial period motions. But before examining the structure of the inertial oscillations, the vertical variation of the low passed currents will be discussed. One hundred percent of the power is passed at a 42 hr period , 50% at a 31 hr period . The technique chosen to investigate the longer period flows was empirical orthogonal function analysis. Perhaps it is appropriate to review this method briefly before stating the results. Detailed discussions of the basis, calculating procedures and utility of the technique are given by Lorenz (1956) and Davis (1977). The major advantage of this procedure is to reduce the number of variables which need to be considered when a large number of data sets are available. Given a set of concurrent data such as that obtained from current meters on a mooring, empirical orthogonal analysis produces an ordered set of amplitude functions (linear statistical estimators or modes) which remove (describe) the maximum amount of variance in the data. Thus, while the shape of each mode (determined by the relative amplitudes at each current meter) is fixed, the amplitude of the mode as a whole mode may vary in time and at different frequencies. The procedures for obtaining the modes involve determining the eigenvalues and eigenvectors of the variance - covariance or correlation matrix of the data. The temporal behaviour of the individual modes is found by multiplying the transposed data matrix by the individual eigenvectors. Table 6 shows the amplitudes, correlations and percent variance for the first two modes. As an example consider the first data set. The first mode describes 43% of the variance in the low passed

TABLE 6. Vertical structure of low frequency variance as described by empirical orthogonal functions. The V, U components are arranged in order of increasing depth.

Time	Site	Total Depth (m)	Sensor Depths (m)	Mode	Percent Variance	Mode Amplitude/Correlation					
						V	U	V	U	V	U
May-July	S709	76	15/30	1	43	-0.58 -0.72	0.49 0.64	-0.42 -0.55	0.51 0.70		
				2	25	-0.52 -0.49	-0.61 -0.60	-0.47 -0.47	-0.39 -0.40		
May-Aug.	ZU	96	25/50/80	1	44	-0.51 -0.68	-0.55 -0.65	-0.38 -0.66	-0.34 -0.63	-0.34 -0.76	-0.25 -0.61
				2	30	-0.55 -0.60	0.74 0.72	-0.32 -0.45	0.05 0.07	-0.16 -0.30	0.14 0.27
Oct.-Jan.	706/OR	75	25/45/60	1	46	-0.42 -0.61	0.69 0.85	-0.44 -0.70	0.36 0.60	-0.15 -0.36	0.05 0.13
				2	38	0.58 0.77	0.43 0.49	0.48 0.69	0.47 0.72	0.12 0.26	0.10 0.25
Oct.-Jan	ZU	163	95/150	1	52	-0.71 -0.94	0.27 0.40	-0.61 -0.87	0.23 0.37		
				2	39	-0.20 -0.23	-0.67 -0.87	-0.30 -0.38	-0.64 -0.87		
Feb.-Mar.	S709	86	31.5/46.5	1	68	-0.76 -0.95	0.39 0.66	-0.51 -0.92	0.09 0.23		
				2	25	-0.35 -0.27	-0.71 -0.73	-0.13 -0.14	-0.60 -0.89		

current meter data for 15 and 30 m, May to July 1980 at the Sedco 709 site. The amplitude of the V component (positive northwards) at 15 m is -0.58 and contains 52% (correlation, -0.72 squared) of the variance of that particular data record. The V components have the same sign, that is, the north-south motion varies in the same direction with time. The U (positive eastwards) components also have the same sign with depth but opposite to that of the V components. This could imply a tendency of the velocity vector to exhibit more variation in two of four quadrants with negative U being associated with positive V or vice-versa. It may also reflect the tendency of wind to vary in preferred directions. The second mode features the same sign for all components. The amount of variance contained in this mode is only slightly less than for mode 1. The structure of the first two modes is similar for all other data sets shown in Table 6 with the order reversed on occasion. In summary, most of the variability exhibited by the components of current has the same sign over depth. The time series plots of mode amplitude (Fig. 6-10) indicate that the variability is exhibited mainly by motions with periods of 2 to 10 days. Remember that tides and high frequency motions have been removed.

The first four data sets shown in Table 6 had variance ratios (northward component/eastward component) ranging from 0.7 to 1.0. The last one had variance ratios of 1.8. The coherences for the U-V components at the same depth for periods of 2 to 10 days for all data in Table 6 were generally quite low (averaging 0.48) and phases were erratic. On the other hand, coherence between like components at different depths on the same mooring in the 2 to 10 day range were somewhat higher averaging 0.60. Generally, coherence was higher (0.70) in the fall and winter seasons than

Fig. 6 Time series of mode 1 and 2 empirical orthogonal functions calculated from the current meter observations taken at 15 and 30 m for the period May to July, 1980.

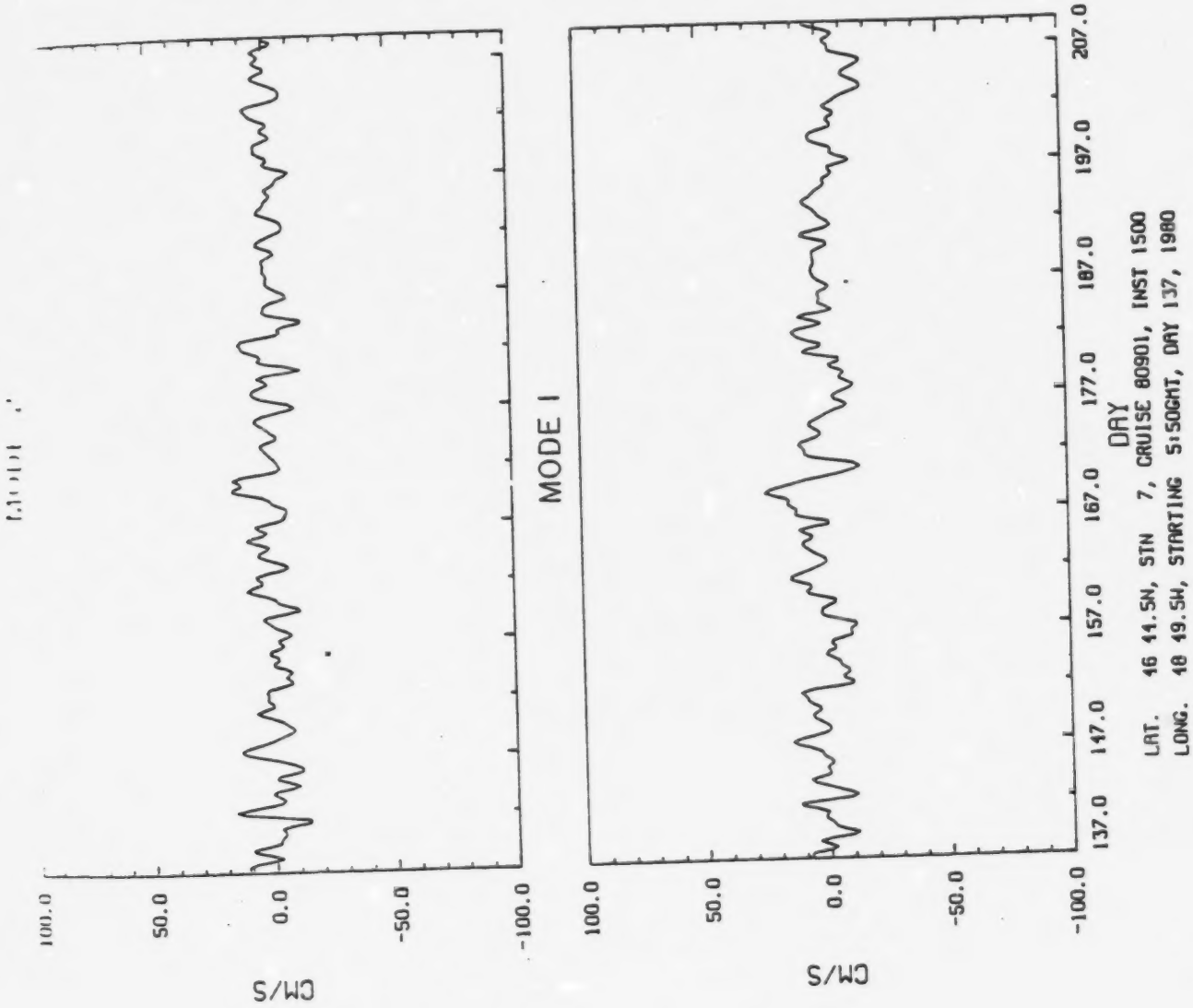


Fig. 7 Time series of mode 1 and 2 empirical orthogonal functions calculated from the current meter observations taken at 25, 50 and 80 m for the period May to August, 1980.

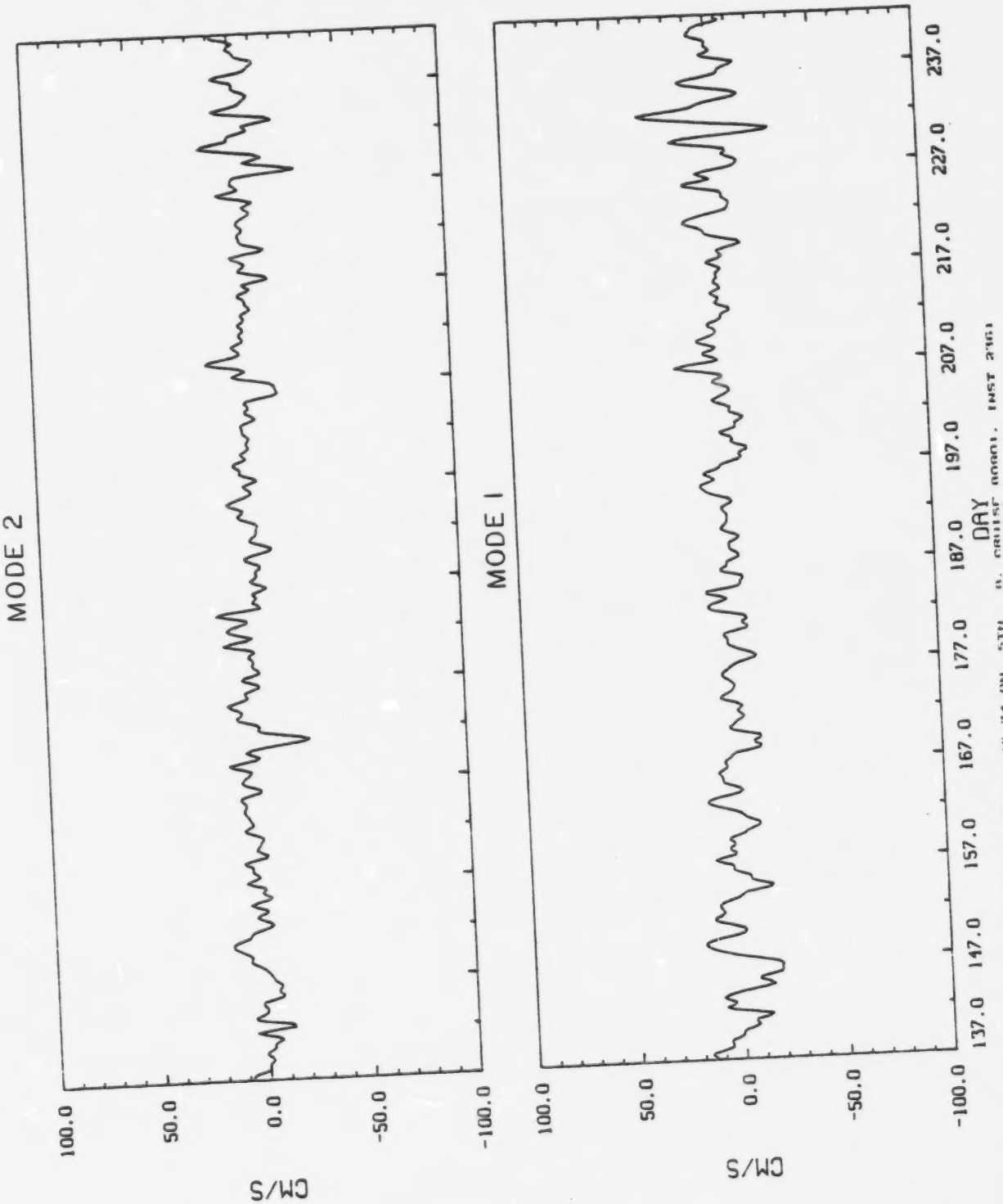


Fig. 8 Time series of mode 1 and 2 empirical orthogonal functions calculated from the current meter observations taken at 25, 45 and 60 m for the period October to January, 1980.

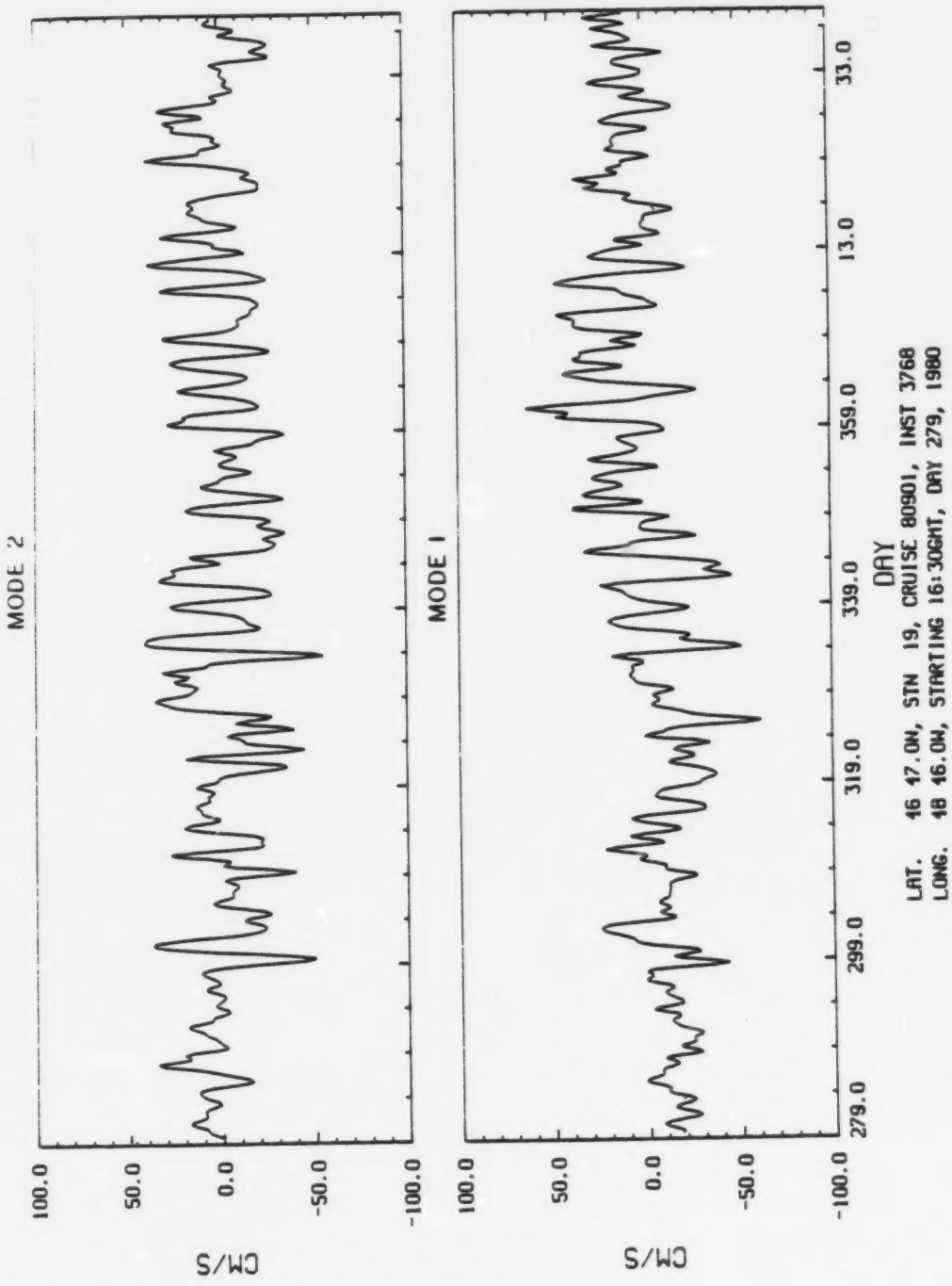


Fig. 9 Time series of Mode 1 and 2 empirical orthogonal functions calculated from the current meter observations taken at 95 and 150 m for the period October to January, 1980.

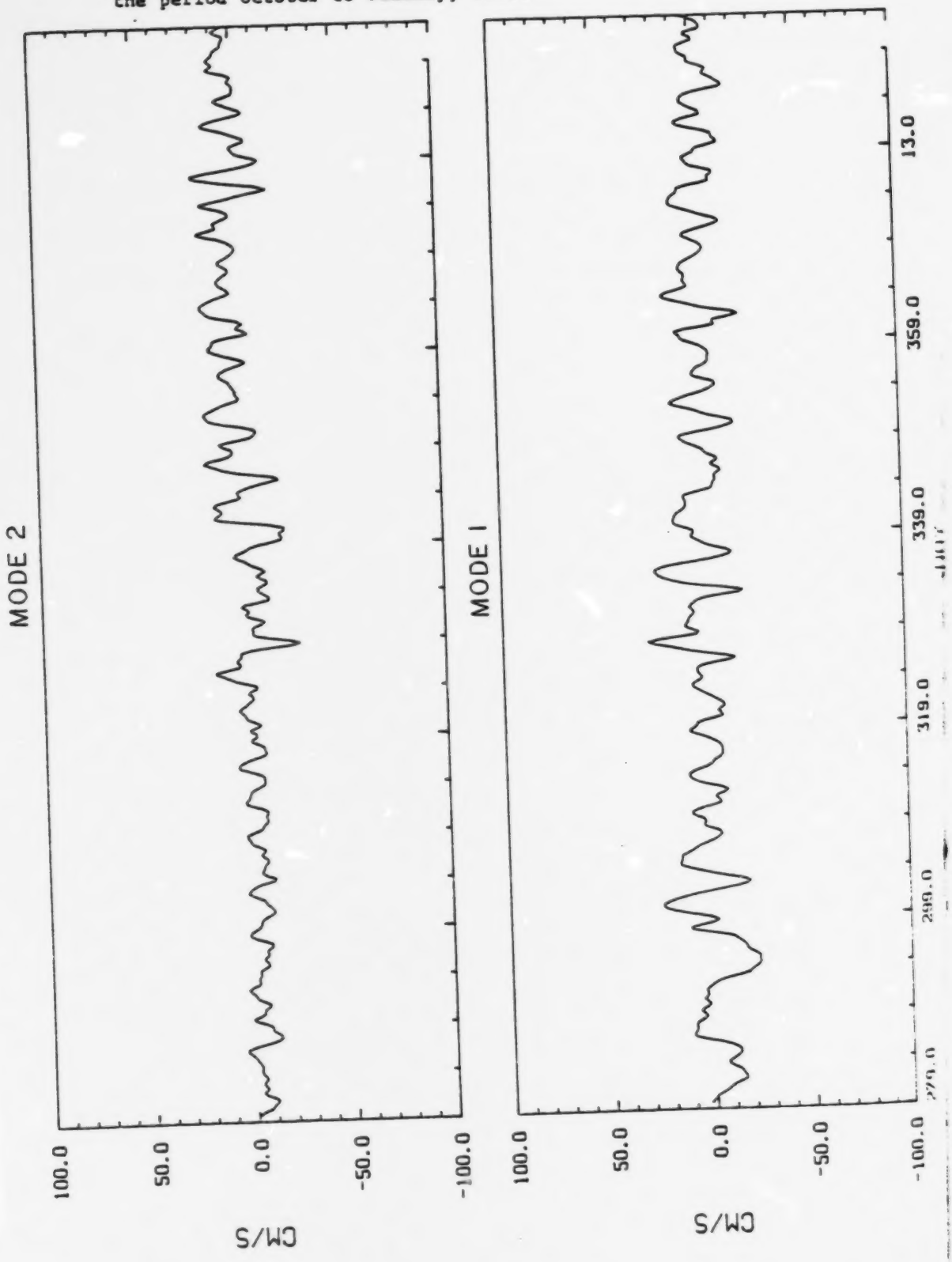
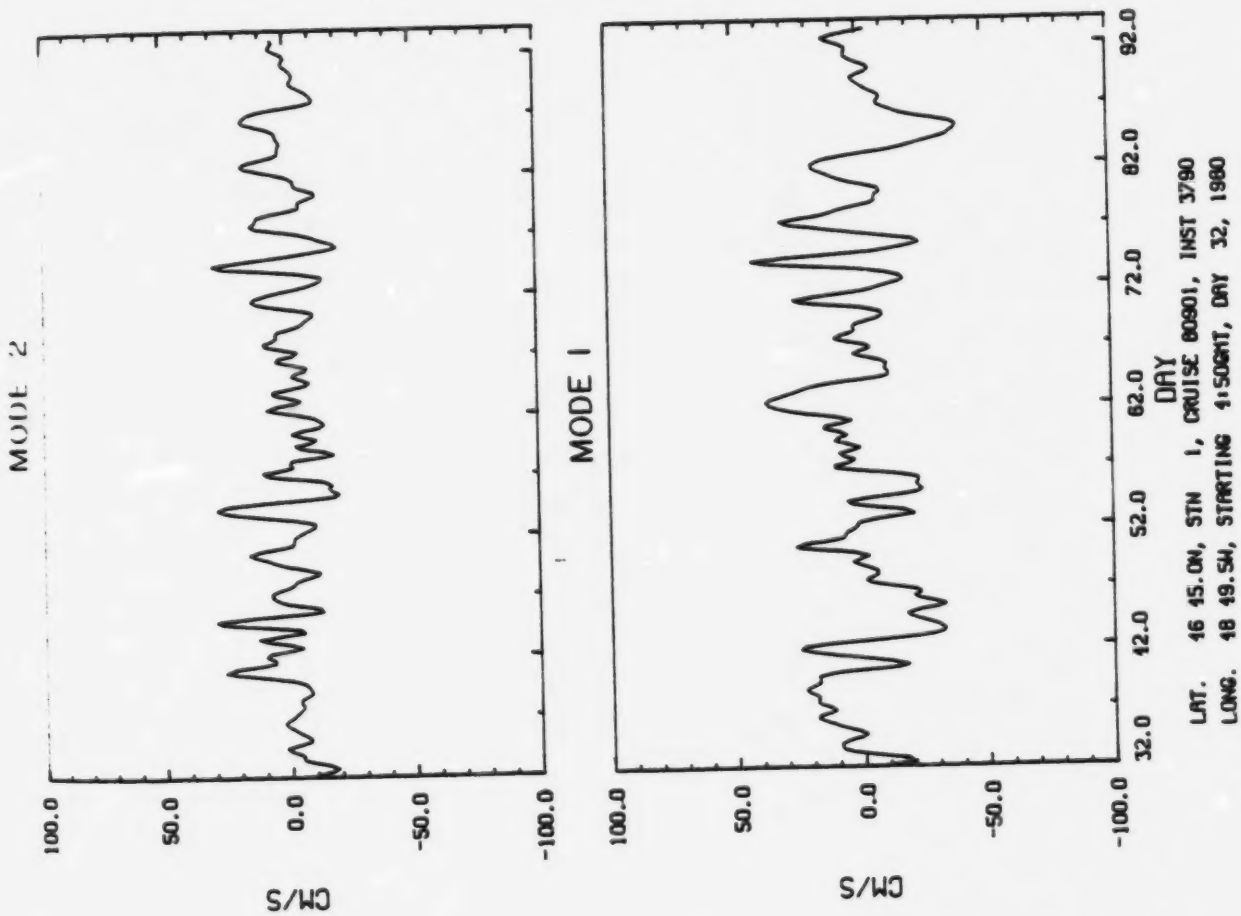


Fig. 10 Time series of mode 1 and 2 empirical orthogonal functions calculated from the current meter observations taken at 31.5 and 46.5 m for the period February to March, 1980. Note that the data from 46.5 m are of doubtful quality.



in spring and summer (0.50). The absolute value of phase differences for fall and winter averaged 27 degrees, that is, motions were approximately in phase. Greater phase differences (averaging 60 degrees) were exhibited during spring and summer periods.

The current meter data were subjected to additional spectral analysis which enabled the inertial period motions to be separated from the tidal currents. The spectral estimate centred at 1.44 cpd with a bandwidth of 0.141 cpd should contain the inertial period motions without leakage from tidal bands. The local inertial frequency is about 1.46 cpd. The results are shown in Table 7 which gives coherences and phases for U-V components at the same depth and like components of velocity at different depths. The numbers in the V-U column are the values ordered according to increasing instrument depth. The values in the V-V and U-U column represent the coherence and phase referenced to the shallowest sensor first.

As may be expected the coherence between V-U components at the same depth was generally very high with V leading U by 90° as expected for inertial period motions. Coherences between like components of velocity were generally lower and quite variable. Phase differences in summer probably reflect the presence of a highly developed thermocline with motions at times being 180° out of phase. Phase differences in fall-winter were generally lower due to the nearly homogeneous conditions that can exist on the shelf. Given that inertial period motions can be quite energetic, these are features that a model of the velocity structure should be able to reproduce.

TABLE 7. Coherence and phase relationships at the inertial period between V and U at the same depths and like components of velocity at different depths. Positive phase means second variable lags first.

Time	Site	Total Depth (m)	Sensor Depths (m)	V-U		V-V			U-U	
				Coh	Phase	Depths	Coh	Phase	Coh	Phase
May-July	S709	76	15	0.99	91	15/30	0.49	109	0.43	106
			30	0.98	92					
May-Aug.	ZU	96	25	0.99	91	25/50	0.51	177	0.51	-178
			50	0.99	93	25/80	0.75	141	0.80	143
			80	0.98	92					
						50/80	0.12	-105	0.16	-101
Oct.-Feb.	706/OR	75	25	0.93	92	25/45	0.92	2	0.91	10
			45	0.90	101	25/60	0.64	51	0.73	46
			60	0.96	88					
						45/60	0.70	44	0.72	31
Oct.-Feb.	ZU	163	95	0.99	89	95/150	0.37	-62	0.35	-54
			150	0.99	90					
Feb.-Mar.	S709	86	31	0.67	82	31/46	0.56	36	0.73	46
			46	0.45	97					

6. WINDS

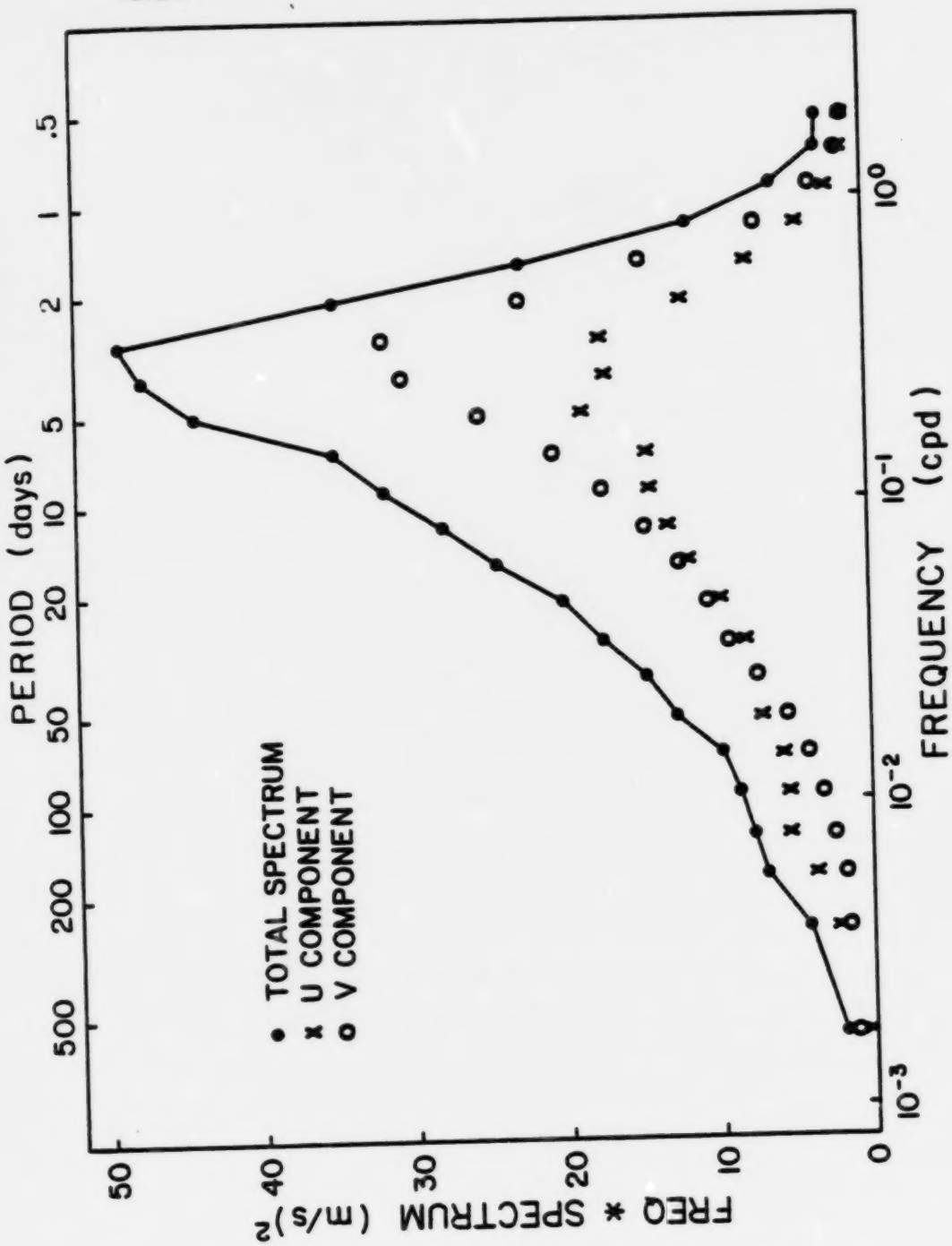
The importance of winds as a forcing mechanism for currents on the continental shelf is a well-established fact. In particular, the increase of current energy in the 2 to 7 d band (Fig. 1-5) for the fall and winter seasons relative to spring and summer is probably attributable to the increase in frequency and intensity of storms for those periods. It is expected that spectral analysis of wind data would show significant energy in the 2 to 7 d range. The geostrophic wind climatology for the years 1946-1978 (Swail and Saulesleja, 1981) was obtained for this purpose. We had also obtained the 1980 wind records from the oil rigs. However, from March 12 to July 12, 13 hourly observations were followed by 11 hour data gaps rendering complete spectral analysis impossible.

Figure 11 shows the total, U(eastwards) and V(northwards) spectra for the geostrophic winds centred at 46.8N, 48.2W. Indeed, the total spectrum shows a peak in the 2 to 7 d range corresponding to the peak in the current meter spectra. The low frequency portion of the spectrum (periods longer than 50 d) has more variance in the U component whereas the band from 1 to 10 d exhibits greater energy in the V component. (We also acquired wind data from Torbay 1963-1980 for comparison purposes. Data editing is incomplete but reliable spectral estimates for the period 1963-1970.5 show the variance at Torbay equal to the variance in the geostrophic wind for periods of 2-100d.)

7. WAVE EFFECTS

It is well known (Pearson et al., 1981; Plansearch Report #3) that current observations taken by instruments with Savonius-type rotors and

Fig. 11 Spectra of the geostrophic wind for the period 1946-1978, 46.8N, 48.2W.



large direction vanes can be severely affected by surface wave-induced noise. All of the data taken at the Hibernia site which we have examined has been collected using Aanderaa current meters which fit the above description. Moreover, Plansearch (see report 3, for example) has noted that the instruments are probably affected by wave velocities. It is of interest then to compute the effects that waves might have on current speeds. This is possible since the Plansearch reports provide time series of significant wave height. Plansearch (pers. comm.) has also provided some information on wave periods.

The wave associated horizontal component of water speed at depth z averaged over a wave period T is given by (Pearson et al., 1981)

$$\overline{V} = (2H/T)e^{-(\sigma^2 z/g)}$$

where g is the gravitational acceleration and $\sigma = 2\pi/T$. The mean and peak significant wave heights were determined by eye from the time series plots presented in these reports. The significant wave height is related to (Neumann and Pierson, 1966) the variance, m_o, of the wave field by

$$H_{sig} = 4(m_o)^{1/2}.$$

The variance of the wave field can then be related to a single wave of amplitude Ho, given by

$$Ho = H_{sig}/2^{1/2}.$$

Table 8 gives $\overline{V}$ at current meters and subsurface buoys (shallowest depth for each grouping) for various time periods. Velocities are calculated for the mean significant wave height, $\overline{H}_{sig}$, the peak significant wave height, H^{P}_{sig}, and the single wave amplitude Ho, which can describe the variance of

TABLE 8. Wave associated horizontal velocities averaged over a wave period.

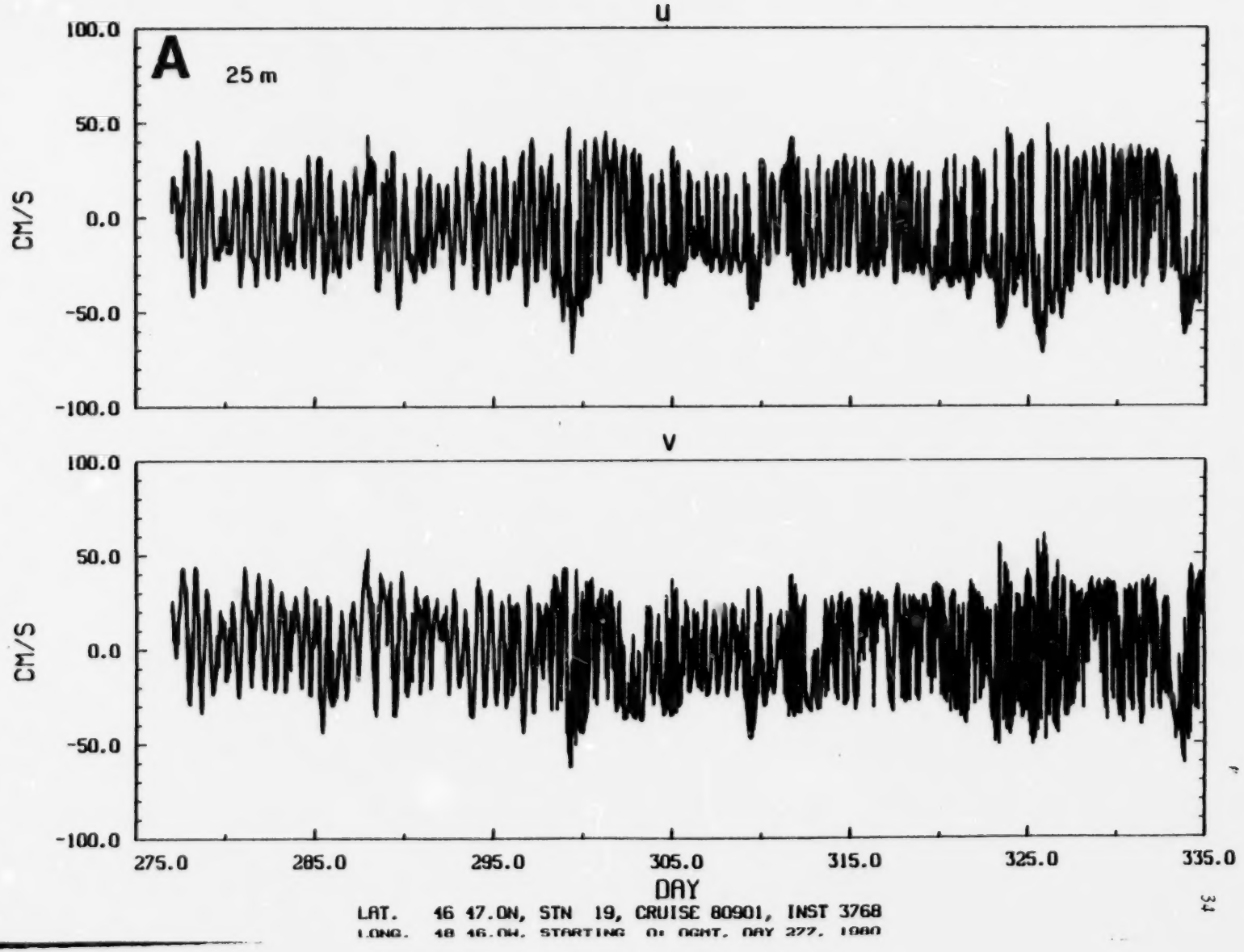
Time	Period (s)	$\overline{H}_{sig}$ (m)	H^{P}_{sig} (m)	H_o (m)	Depth (m)	$\overline{V}_{sig}$ (m/s)	V_{sig} (m/s)	V_o (m/s)
Feb.-March 1980	9	3.5	7.1	2.5	27	0.20	0.41	0.15
					31.5	0.16	0.33	0.12
					46.5	0.08	0.16	0.06
May-June	9	2.0	3.5	1.4	10	0.27	0.47	0.19
					15	0.22	0.37	0.15
					30	0.10	0.18	0.07
					20	0.16	0.29	0.12
					25	0.13	0.22	0.09
June-July	9	1.7	3.2	1.2	10	0.24	0.41	0.17
					15	0.19	0.32	0.13
					30	0.09	0.16	0.06
					20	0.14	0.25	0.11
					25	0.11	0.19	0.08
August	9	1.7	4.5	1.2	20	0.14	0.37	0.11
					25	0.11	0.29	0.08
Oct.-Dec.	12	3.2	7.3	2.3	20	0.31	0.70	0.22
					25	0.27	0.61	0.19
					45	0.15	0.35	0.11
					60	0.10	0.23	0.07
					30	0.23	0.53	0.16
					35	0.20	0.46	0.14

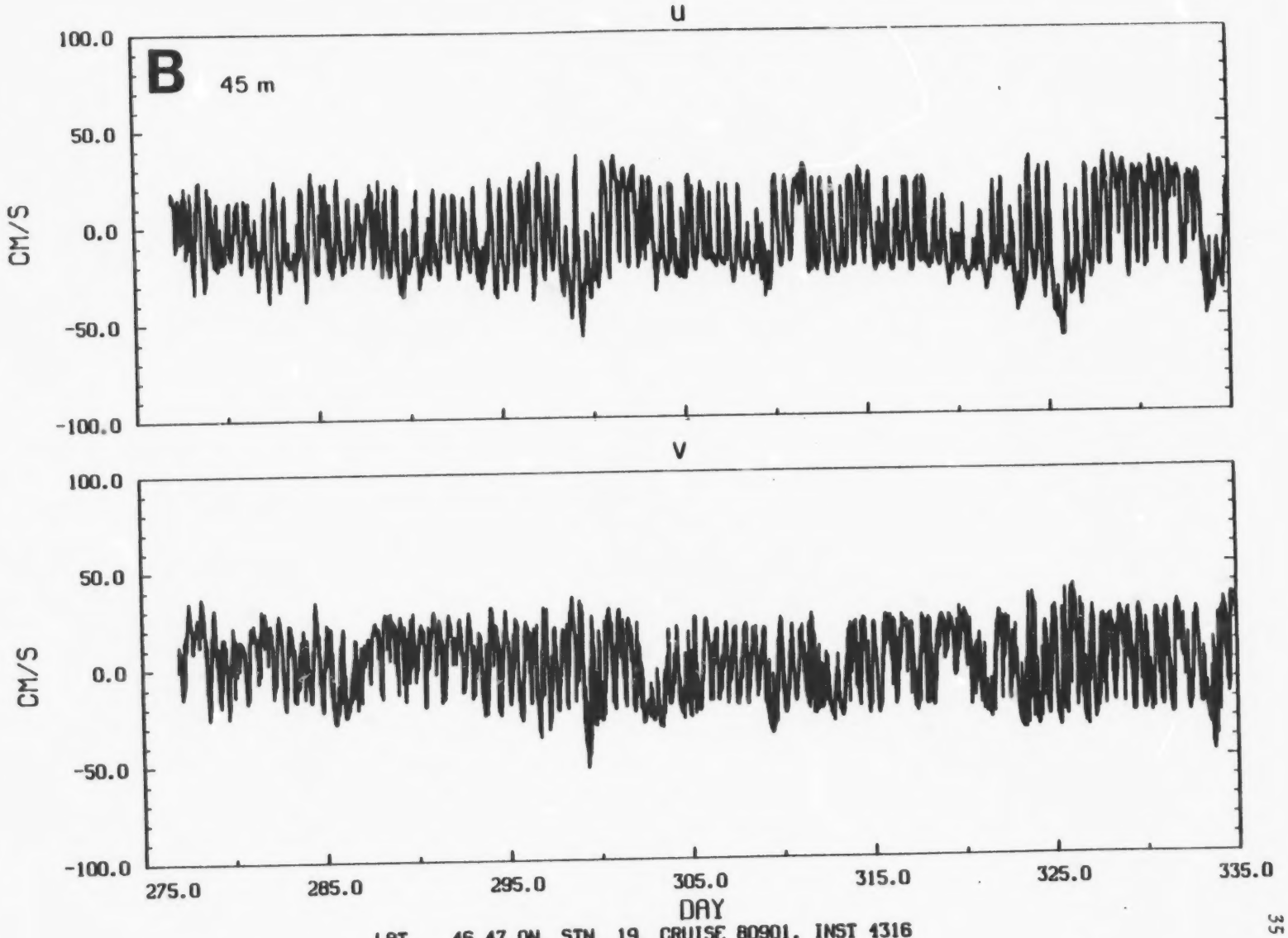
the wave field.

The results indicate that wave-induced motion could significantly affect the measurements over the entire year but especially over the fall and winter periods. It is quite possible that the wave motion could affect the low frequency variability since the wave fields are, of course, strongly influenced by the variation of the wind (see Section 3.0).

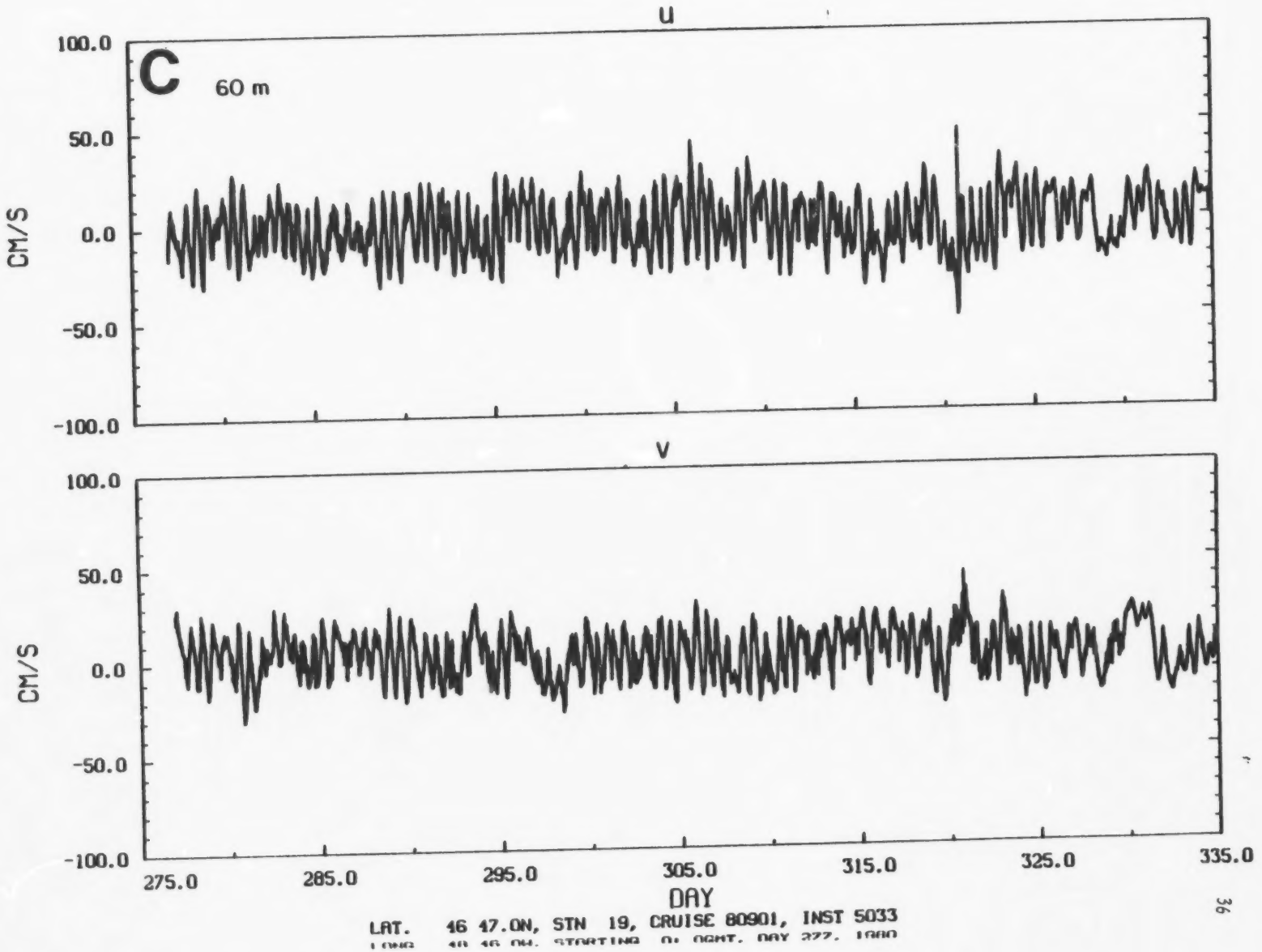
The horizontal wave-induced velocities could also cause significant mooring motion which in turn could degrade the current measurements. Figure 12(A)-(F) show time series of rate, direction, U and V at the Sedco 706 site, October to December 1980. It is apparent that the record contains significant high frequency energy largely due to rapid fluctuations in direction. P. Keenan (pers. comm.) has indicated that fluctuations of ±45° can be induced in the compass of the Aanderaa current meter by subjecting the instrument to small amounts of vibration. E. Daddio (Evans-Hamilton, pers. comm.) has reported similar observations from the December to February data when changes in direction by up to 180° over a 10 minute sampling interval led to current fluctuations of ±0.4 m/s. The spectra (Fig. 4) of the data shown in Fig. 12 feature significant high frequency energy which decreases with depth. Plansearch Report No. 8 (their Fig. 12) shows four occasions when significant wave height was greater than 6 m. These events were centred on Julian days 299, 323, 326 and 334. It is evident from Fig. 12(A)-(F) that these times corresponded to significant levels of high frequency motion in the current records. Note, that the highest levels of energy appear to occur on these occasions for the shallowest mooring. Examination of the data taken in February to March 1980 showed similar behaviour. It is apparent then that the data gathered at

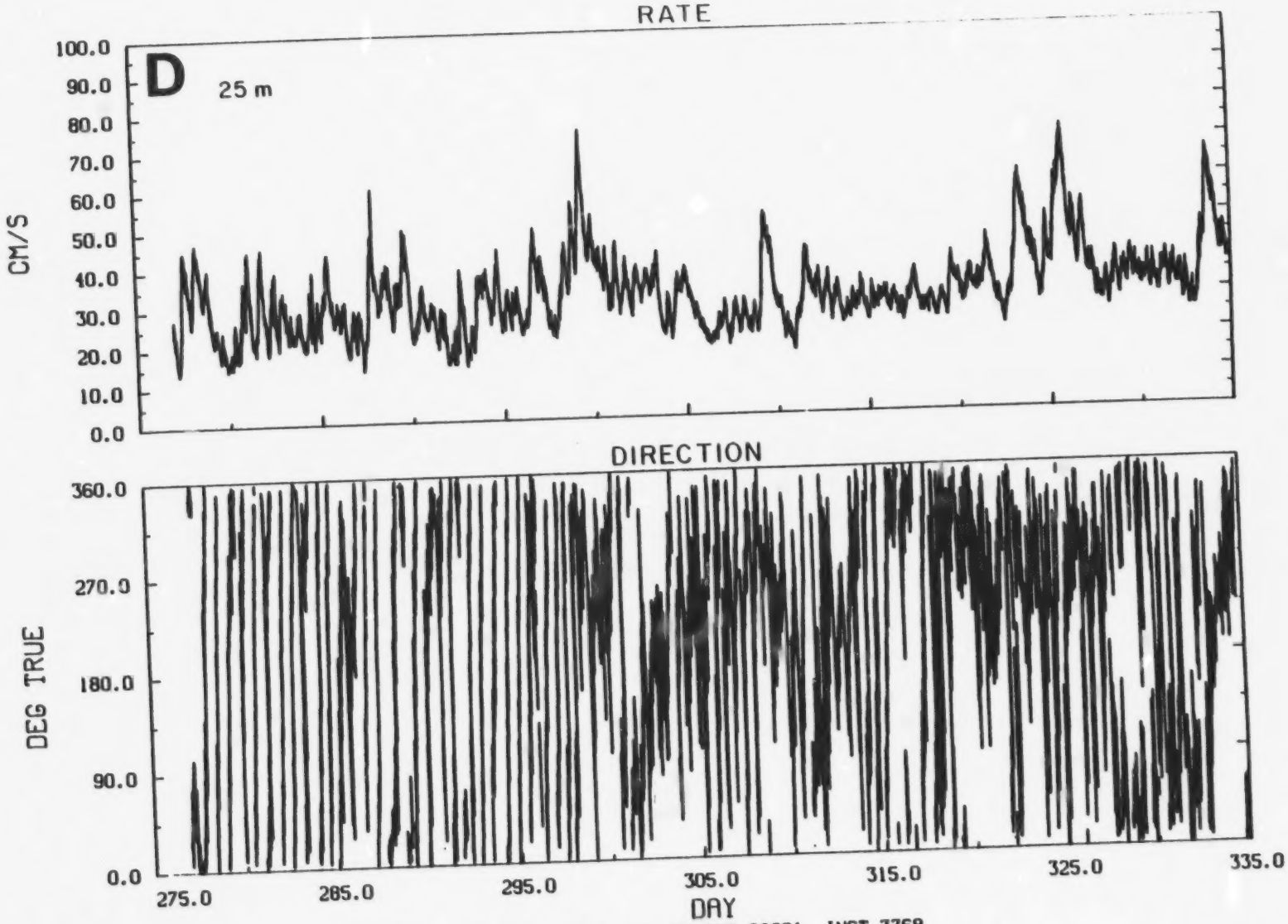
Fig. 12 Time series of current meter data at the Sedco 706 site, October to December, 1980. (A) u,v at 25 m. (B) u,v at 45 m. (C) u,v at 60 m. (D) R,D at 25 m. (E) R,D at 45 m. (F) R,D at 60 m.


u
A
25 m
100.0
50.0
0.0
-50.0
-100.0
CM/S
v
100.0
50.0
0.0
-50.0
-100.0
CM/S
275.0
285.0
295.0
305.0
315.0
325.0
335.0
DAY
LAT. 46 47.0N, STN 19, CRUISE 80901, INST 3768
LONG. 48 46.0W, STARTING 0: 0GMT, DAY 272, 1980

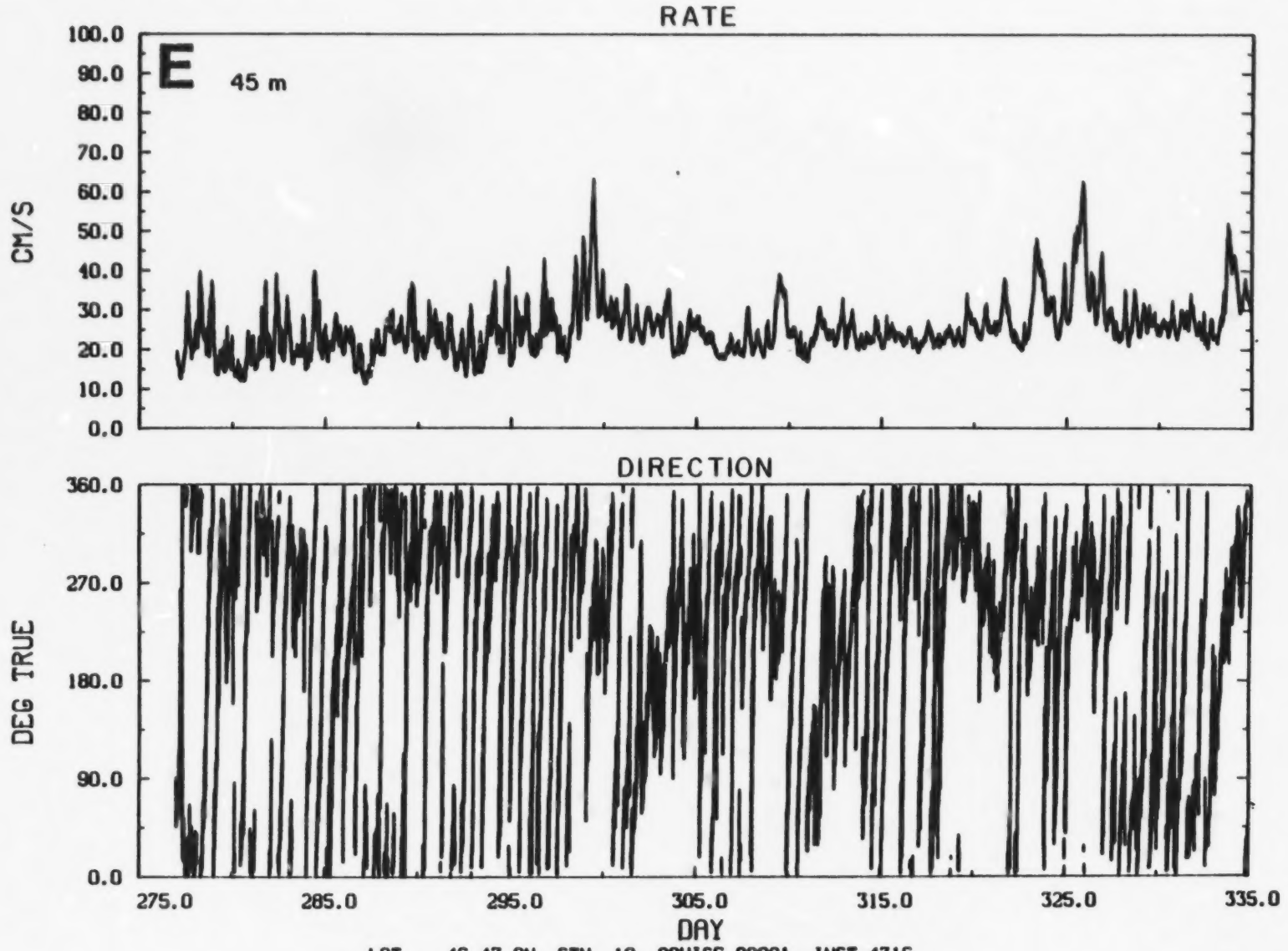


LAT. 46 47.0N, STN 19, CRUISE 80901, INST 4316
LONG. 48 46.0W, STARTING 0: 0GMT, DAY 277, 1980

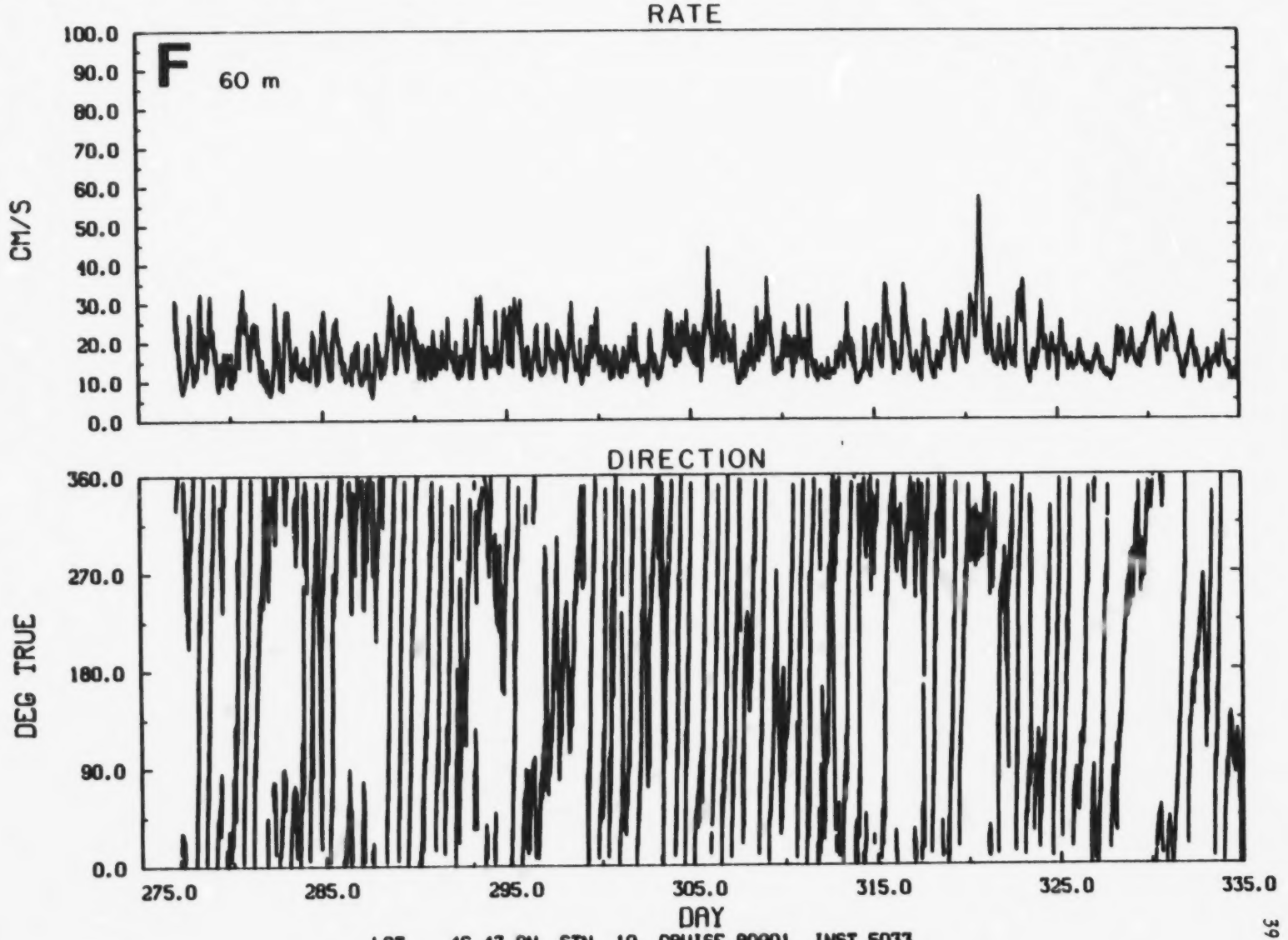

u
C
60 m
100.0
50.0
0.0
-50.0
-100.0
CM/S
v
100.0
50.0
0.0
-50.0
-100.0
CM/S
275.0
285.0
295.0
305.0
315.0
325.0
335.0
DAY
LAT. 46 47.0N, STN 19, CRUISE 80901, INST 5033



LAT. 46 47.0N, STN 19, CRUISE 80901, INST 3768
LONG. 48 46.0W, STARTING 0: 0GMT, DAY 277, 1980



LAT. 46 47.0N, STN 19, CRUISE 80901, INST 4316
LONG. 48 46.0W, STARTING 0: 00GMT, DAY 277, 1980



LAT. 46 47.0N, STN 19, CRUISE 80901, INST 5033
LONG. 48 46.0W, STARTING 0: 0GMT, DAY 277, 1980

the Hibernia site have been affected by the waves either directly (orbital velocities spinning up rotors) or through mooring motion. This could lead to difficulty in determining extreme currents or in verifying models of wind-induced currents.

8. MODELLING WIND EFFECTS

The results from sections 3, 5 and 6 led one to conclude that wind is an important forcing mechanism for low frequency current generation at the Hibernia site. Two approaches can be used to define more precisely the effects wind might have on water motion. The first is a dynamical approach and the second is statistical. We shall consider simple momentum balances for the Hibernia site and compare the results from this model to the observations. If a sufficiently accurate model can be built then long time series of wind (see Section 6) could be used to generate current speed and direction statistics based on wind-induced motions. The addition of tidal currents and estimates of motions due to other causes (instabilities in the Labrador Current, for example) could then allow a more accurate prediction of long term current extremes and distribution.

An alternative to dynamical modelling is the statistical approach. In Section 5, empirical orthogonal functions were introduced and it was found that the first two modes contained most of the variance of the low frequency record. These modes showed a time variation similar to that expected in the wind field. The modal amplitudes can be regressed on the wind components and the validity of the statistical model assessed. Using the empirical modes of currents reduces the number of variables from six (maximum) to two. A good statistical model could be used to predict

current distributions from long time series of wind.

Before examining the results of these approaches it should be stressed again that (i) wind data from the rigs were measured at two different heights (January 1 to March 6 at 27 m, March 6 to December 31 at 76 m); (ii) These data have gaps (from March 12 to July 12, 13 hours of data alternated with 11 hour gaps; (iii) The existing geostrophic wind climatology (Swail and Saulesleja, 1981) may be inadequate for hindcasting currents with either of the models. An improved climatology may be available as a result of studies related to Hibernia which are being conducted by the Atmospheric Environment Service. (iv) The current data may be inadequate due to errors (Section 7) or lack of coverage (we have contemporaneous coverage of currents (3 depths) and winds (no gaps) for August and October to December). (v) Proper use of the meteorological data would involve reducing the 27 m, 76 m and geostrophic winds to a common denominator. This is not a simple task since, for example, Swail and Saulesleja report that the ratio of anemometer wind to geostrophic wind can range 0.40 to 0.90 depending on a number of factors. There are, as we shall see, other difficulties as well.

A simple dynamical model has been considered for the wind driven currents at the Hibernia site. The terms retained in the equations of motion are acceleration, Coriolis force and wind forcing. The are given by

$$(\partial u/\partial t) - fv = (\tau^x/\rho h)$$

$$(\partial v/\partial t) + fu = (\tau^y/\rho h)$$

where u and v are the velocity components, $f = 1.06 \times 10^{-4}$/s is the Coriolis parameter, τ is the wind stress, ρ is the water density, and h is the depth

of the mixed layer. The wind stress acts like a body force over a slab of water of thickness, h, which was taken as the depth of the mixed layer. The model is similar to that of Pollard and Millard (1970) but neglects friction. While it is intended only to integrate the model for a short time, the results of this investigation might indicate whether this approach should be pursued.

Six events were considered and are shown in Table 9. Where a wind period is given, wind speed has the form A sin ωt. This formulation allowed analytical solutions to be derived, otherwise, a finite difference approach could have been used with the wind data as recorded. The wind direction was allowed to vary in a similar fashion. The depth of the mixed layer was based on available temperature and salinity data. Conversion of wind to wind stress was based on the formula of Smith and Banke (1975). In all cases, the initial conditons had both components of current velocity equal to zero.The results are shown in Fig. 13A-F. Note that tides have been removed from these data through harmonic analysis.

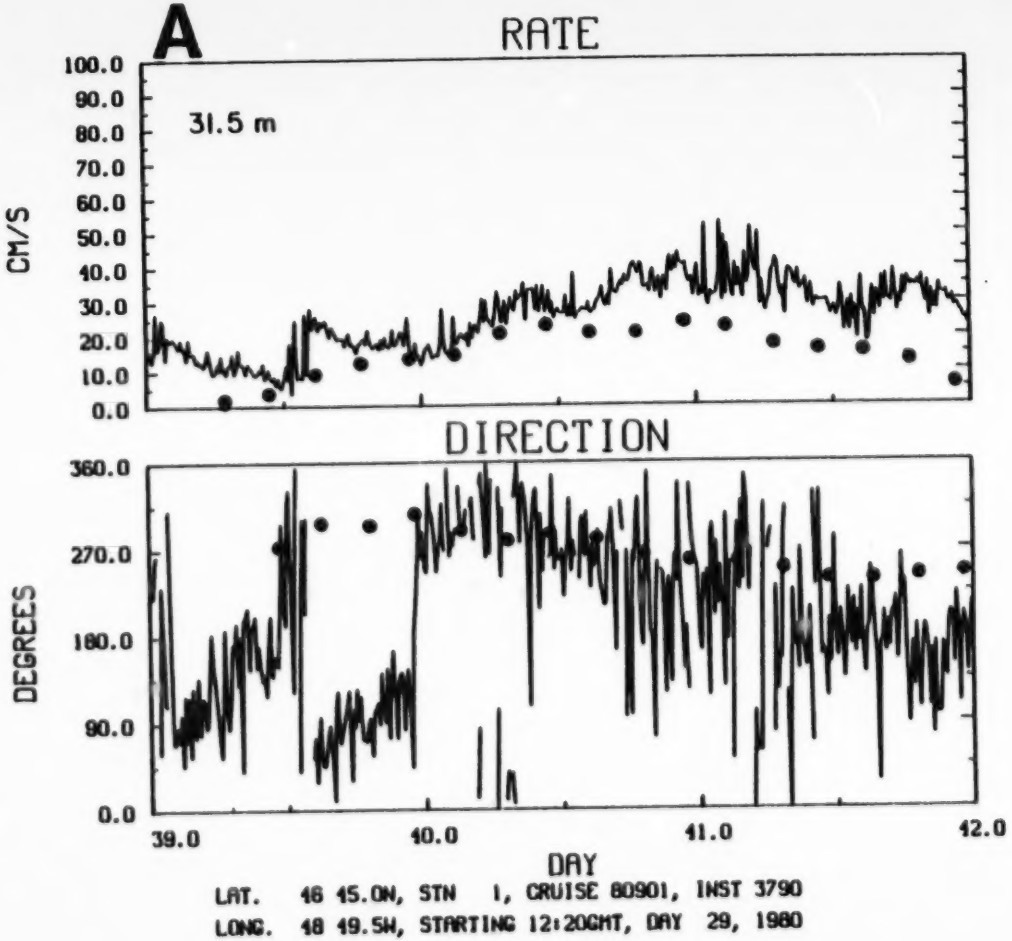
Event A, Fig. 13(A). The entire water column was well mixed for this event and for the next two as well. Currents are underestimated by as much as 20 cm/s. Directions agree to within ±45° most of the time. The observations of the instrument at 46.5 m are in doubt and are not incluced. Peak significant wave height was 6 m during this time period.

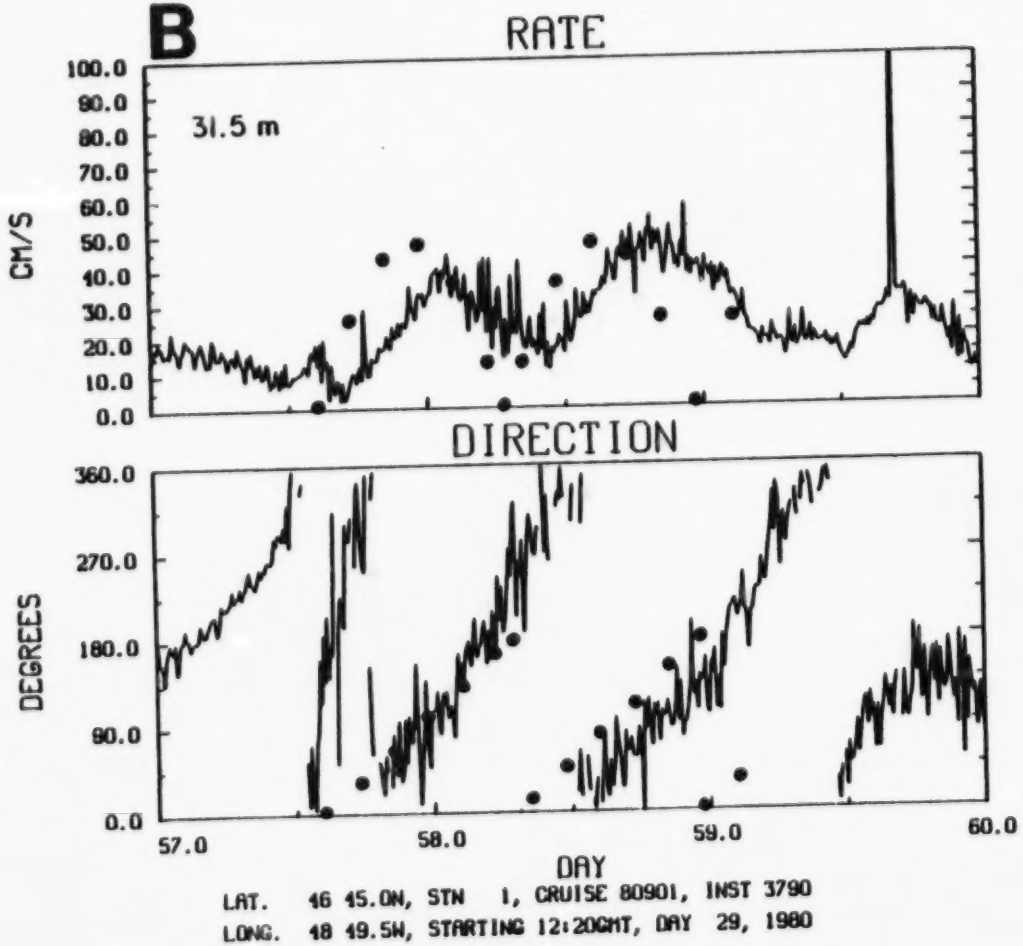
Event B, Fig. 13(B). Current agreement for the upper meter is very good. The apparent temporal offset of about 3 h may be due to incorrect start times. Direction agreement is reasonable with the model predicting a current confined to 0-180°T. The direction data cover a full circle but exhibit a change of slope at about 180°. Peak significant wave height was 7 m.

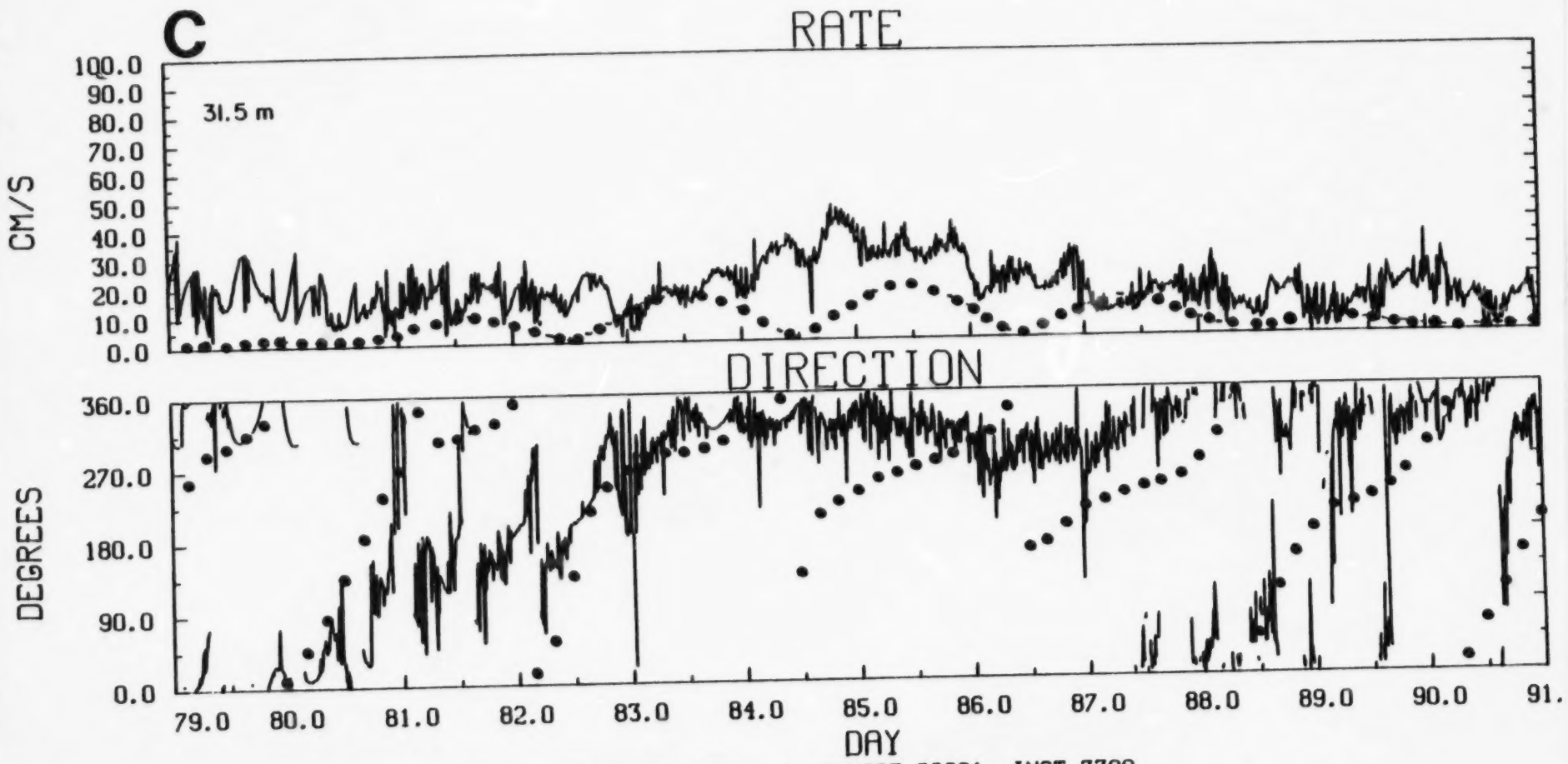
TABLE 9. Characteristics of winds for six time periods, 1980.

Event	Julian Day	Wind Amplitude (m/s)	Period (d)	Direction to (°T)	Mixed Layer Depth (m)
A	39-42	25	6	247.5 to 112.5 in 3 d	70
B	57-60	25, constant for 1.5 d	-	360	70
C	79-90	17.5 5.0	24 2	270 to 90 in 12 d	70
D	144-147	20, constant for 4 h 10, constant for 3 d	- -	315 to 360 360	40
E	183-184	18.3, constant for 14 h 0, constant for 34 hr	- -	360	22.5
F	229-231	19	4 d	315 to 135 in 2 d	25

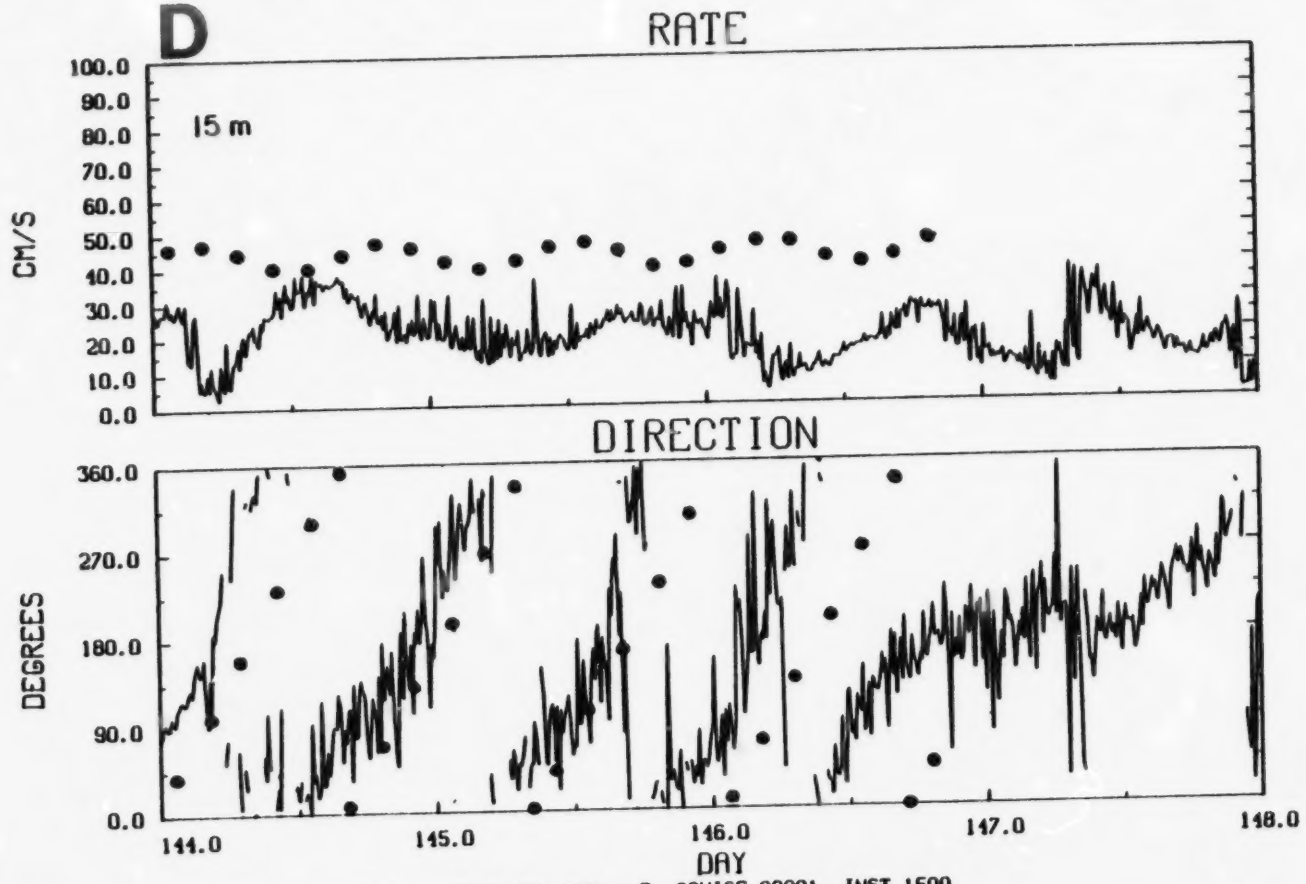
Fig. 13 Comparison of observed current rate and direction with model results. (A) 31.5 m, Julian day 39-42. (B) 31.5 m, Julian day 57-60. (C) 31.5 m, Julian day 79-91. (D) 15 and 30 m at Sedco 709 site; 25, 50 and 80 m at Zapata Ugland site, Julian day 144-148. (E) 15, 30 and 60 m at Sedco 709 site; 25, 50 and 80 m at Zapata Ugland site, Julian day 183-185. (F) 25, 50 and 80 m at Zapata Ugland site, Julian day 228-233. Model results are shown as dots.


A
RATE
31.5 m
CM/S
100.0
90.0
80.0
70.0
60.0
50.0
40.0
30.0
20.0
10.0
0.0
DIRECTION
DEGREES
360.0
270.0
180.0
90.0
0.0
39.0
40.0
41.0
42.0
DAY
LAT. 46 45.0N, STN 1, CRUISE 80901, INST 3790
LONG. 48 49.5W, STARTING 12:20GMT, DAY 29, 1980

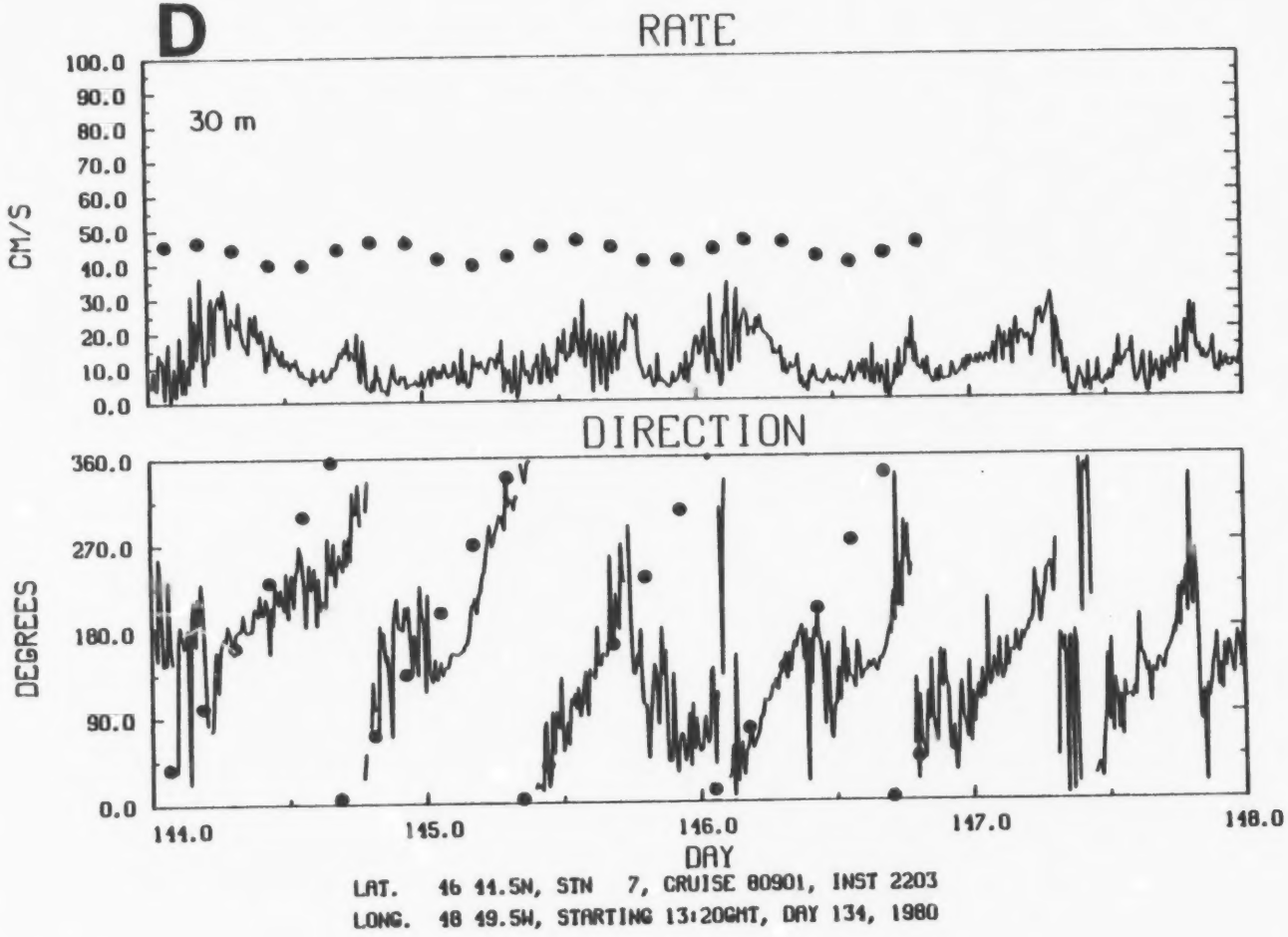

B
RATE
31.5 m
CM/S
100.0
90.0
80.0
70.0
60.0
50.0
40.0
30.0
20.0
10.0
0.0
DIRECTION
DEGREES
360.0
270.0
180.0
90.0
0.0
57.0
58.0
59.0
60.0
DAY
LAT. 46 45.0N, STN 1, CRUISE 80901, INST 3790
LONG. 48 49.5W, STARTING 12:20GMT, DAY 29, 1980



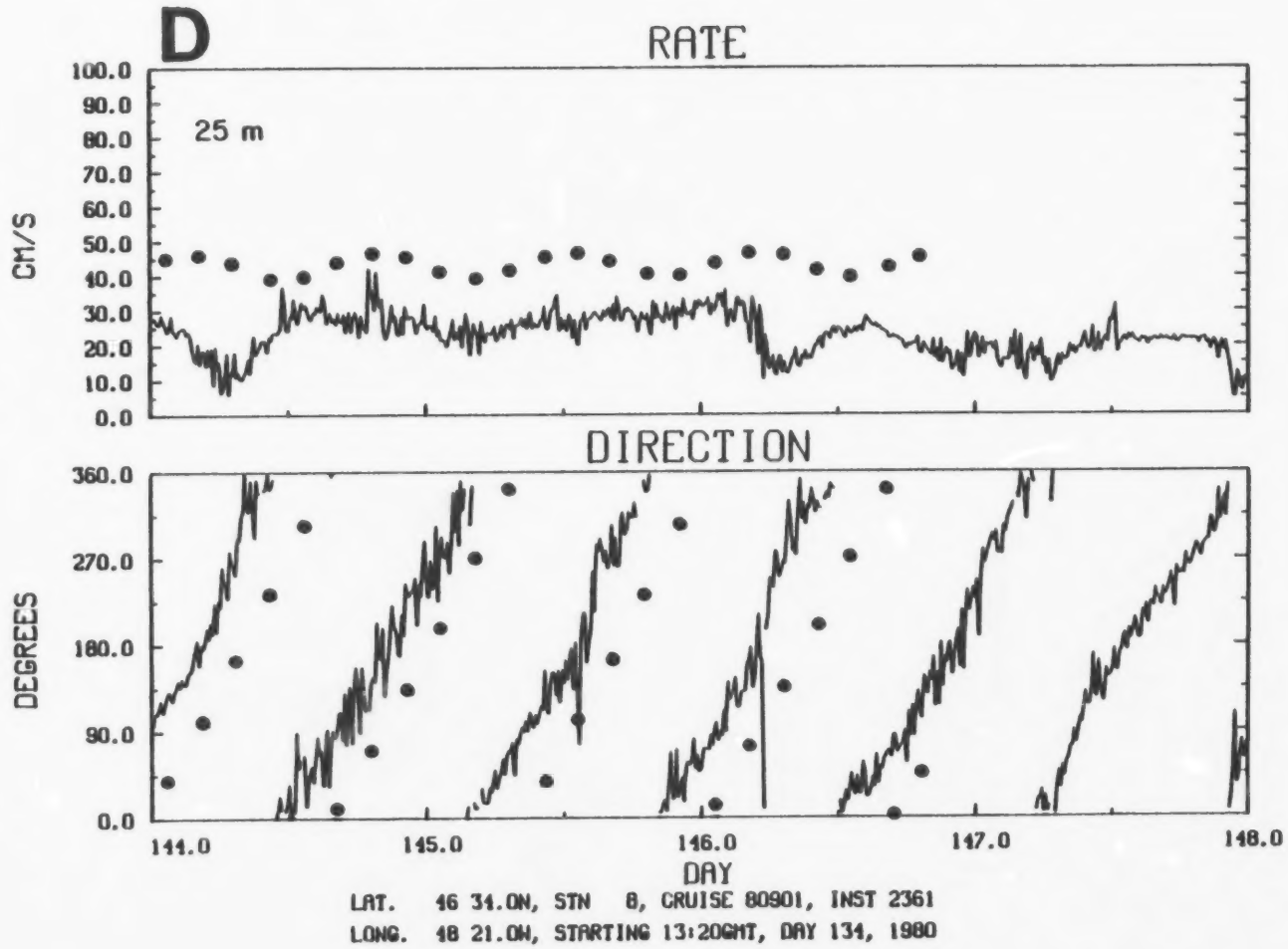
LAT. 46 45.0N, STN 1, CRUISE 80901, INST 3790
LONG. 48 49.5W, STARTING 12:20GMT, DAY 29, 1980

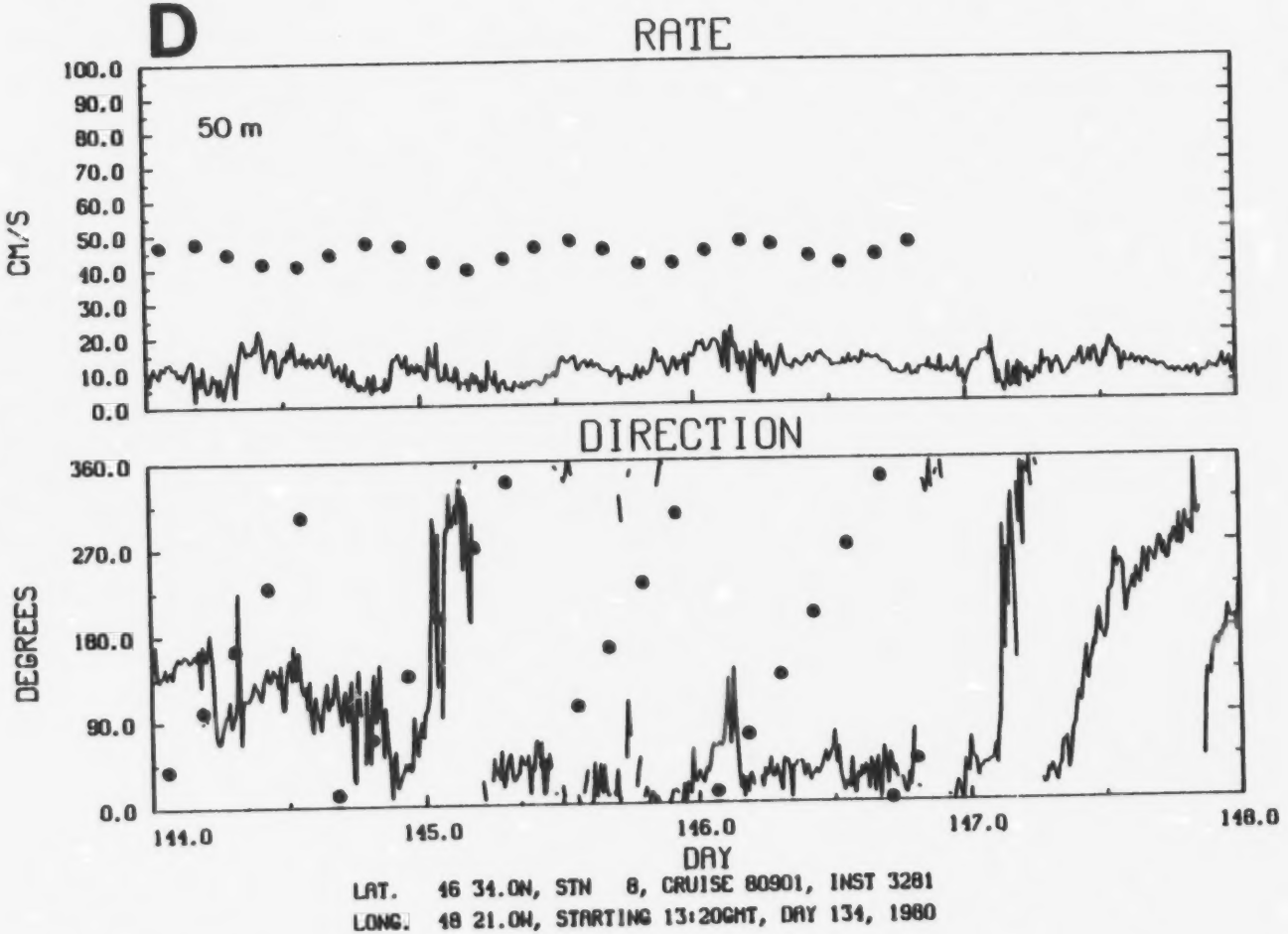


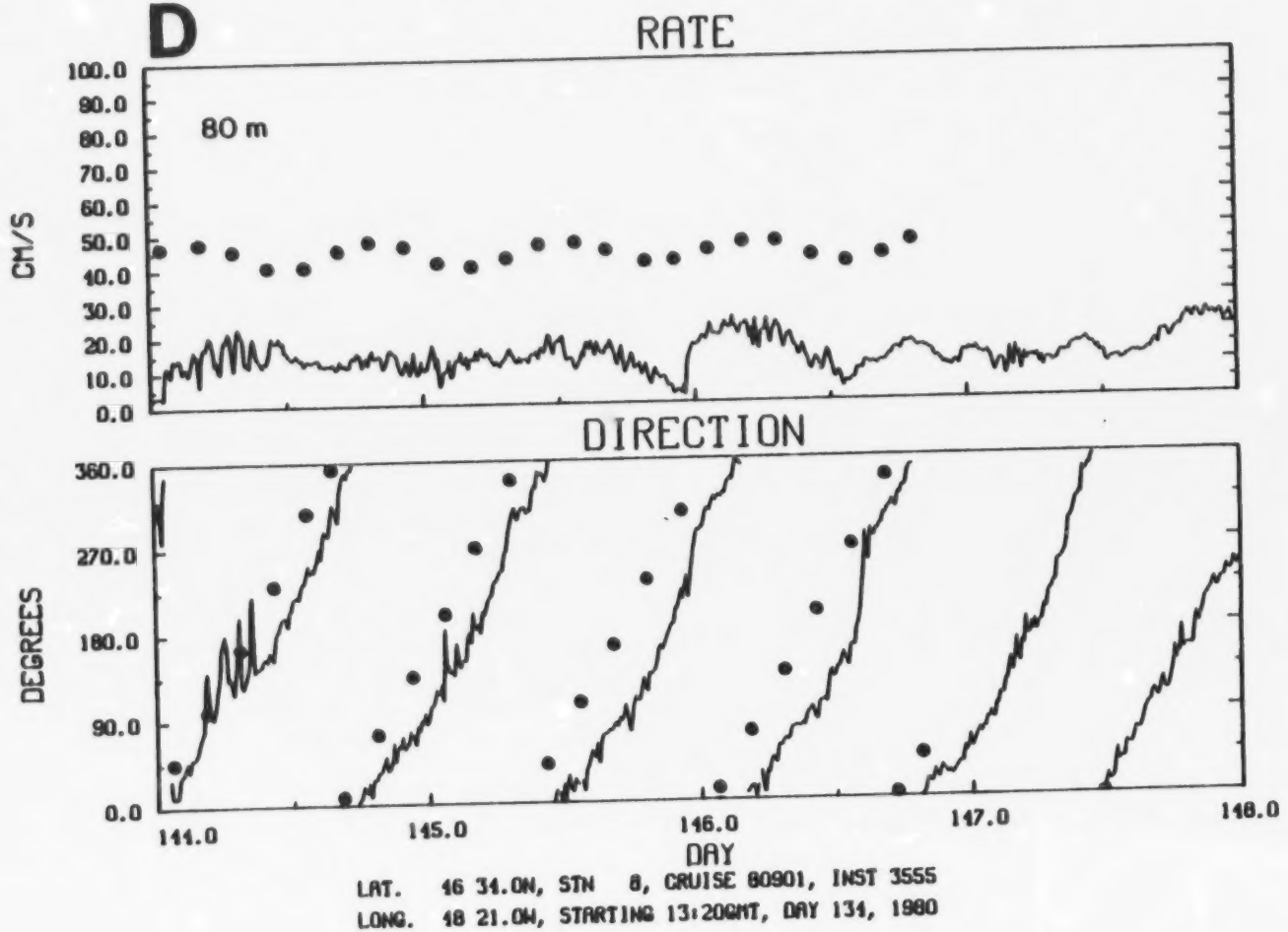
LAT. 46 44.5N, STN 7, CRUISE 80901, INST 1500
LONG. 48 49.5W, STARTING 13:20GMT, DAY 134, 1980

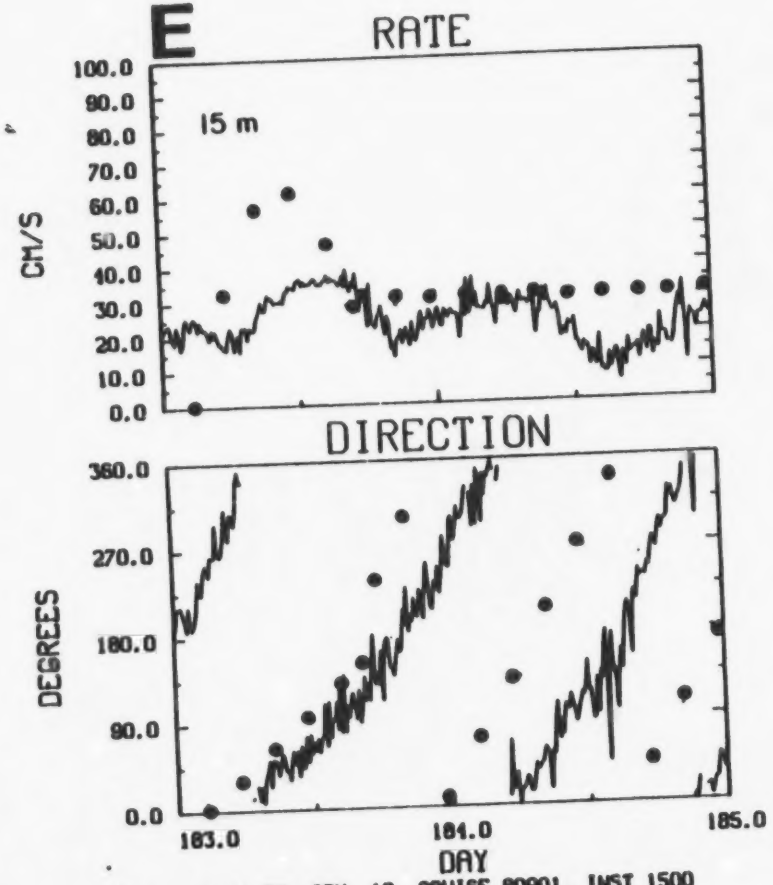


LAT. 46 44.5N, STN 7, CRUISE 80901, INST 2203
LONG. 48 49.5W, STARTING 13:20GMT, DAY 134, 1980


D
RATE
25 m
CM/S
100.0
90.0
80.0
70.0
60.0
50.0
40.0
30.0
20.0
10.0
0.0
DIRECTION
DEGREES
360.0
270.0
180.0
90.0
0.0
144.0
145.0
146.0
147.0
148.0
DAY
LAT. 46 34.0N, STN 8, CRUISE 80901, INST 2361
LONG. 48 21.0N, STARTING 13:20GMT, DAY 134, 1980


D
RATE
50 m
CM/S
100.0
90.0
80.0
70.0
60.0
50.0
40.0
30.0
20.0
10.0
0.0
DIRECTION
DEGREES
360.0
270.0
180.0
90.0
0.0
144.0
145.0
146.0
147.0
148.0
DAY
LAT. 46 34.0N, STN 8, CRUISE 80901, INST 3281
LONG. 48 21.0W, STARTING 13:20GMT, DAY 134, 1980


D
RATE
80 m
CM/S
100.0
90.0
80.0
70.0
60.0
50.0
40.0
30.0
20.0
10.0
0.0
DIRECTION
DEGREES
360.0
270.0
180.0
90.0
0.0
144.0
145.0
146.0
147.0
148.0
DAY
LAT. 46 34.0N, STN 8, CRUISE 80901, INST 3555
LONG. 48 21.0W, STARTING 13:20GMT, DAY 134, 1980


E
RATE
15 m
CM/S
100.0
90.0
80.0
70.0
60.0
50.0
40.0
30.0
20.0
10.0
0.0
DIRECTION
DEGREES
360.0
270.0
180.0
90.0
0.0
183.0
184.0
185.0
DAY
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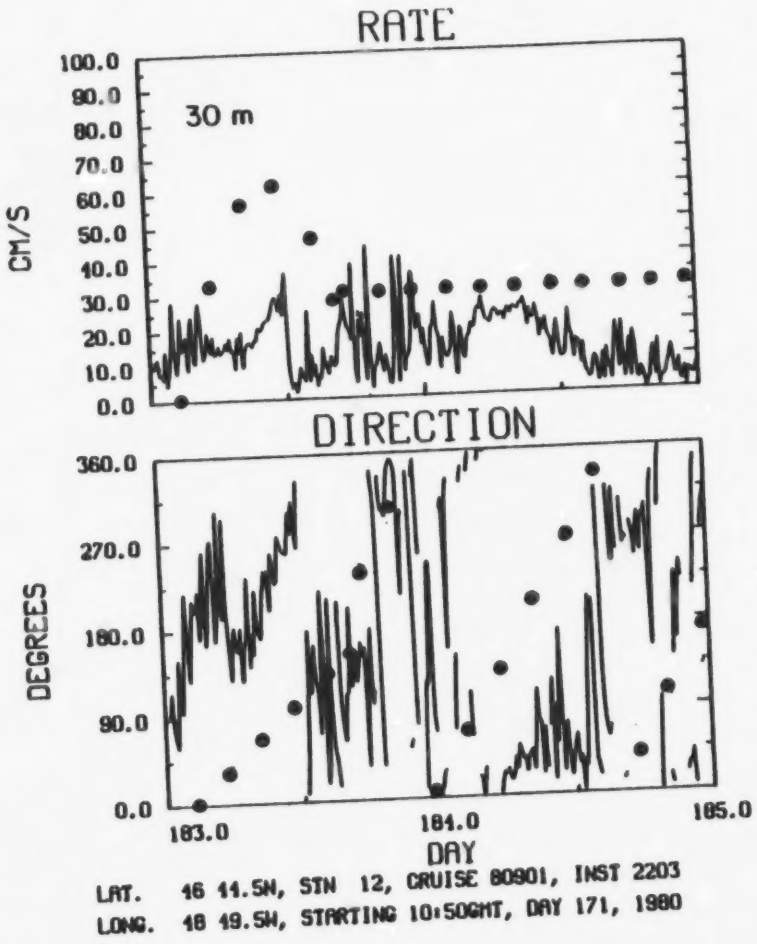
LONG. 48 49.5W, STARTING 10:50GMT, DAY 171, 1980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CM/S
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80.0
70.0
60.0
50.0
40.0
30.0
20.0
10.0
0.0
DIRECTION
DEGREES
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270.0
180.0
90.0
0.0
183.0
184.0
185.0
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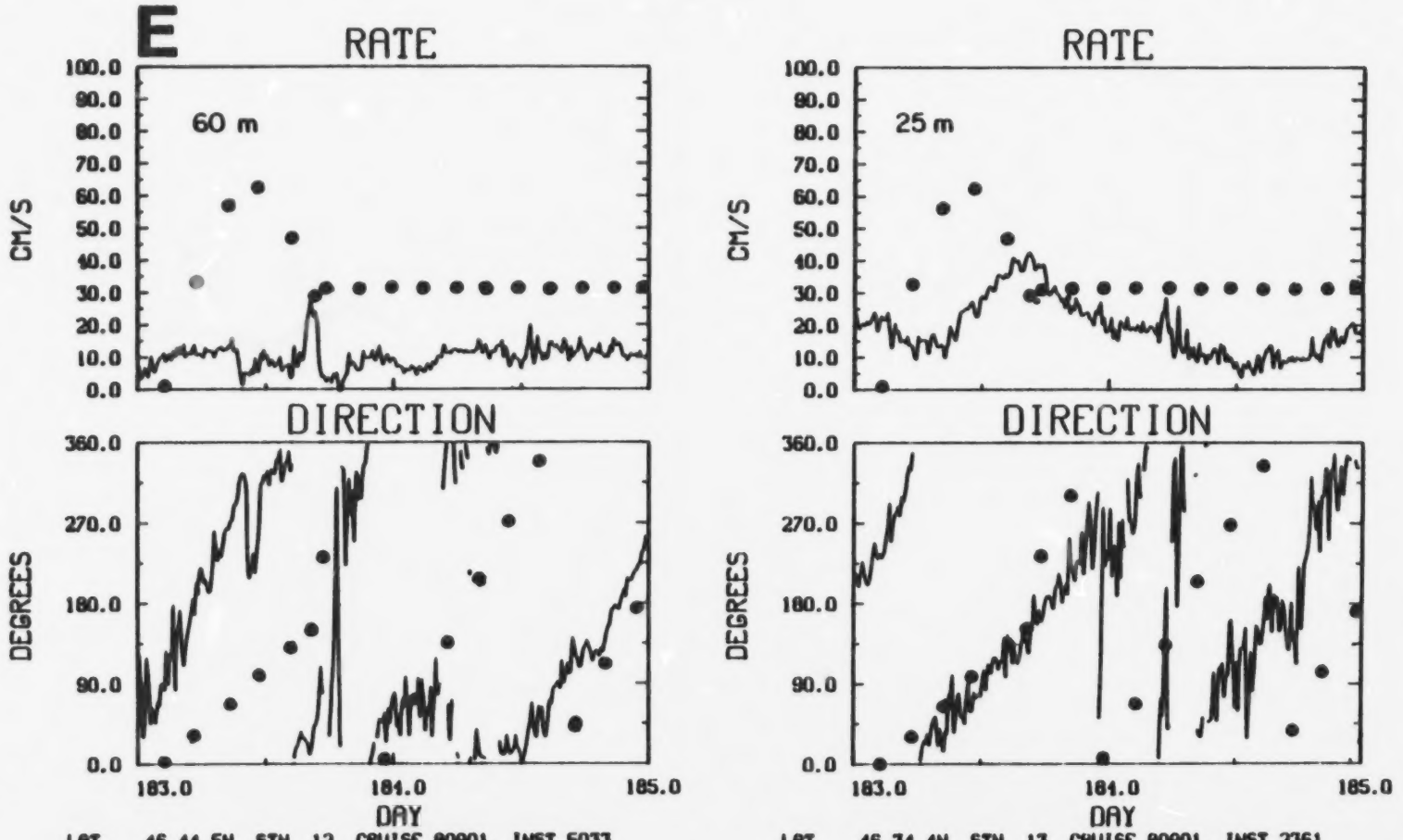
E
RATE
60 m
CM/S
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90.0
80.0
70.0
60.0
50.0
40.0
30.0
20.0
10.0
0.0
DIRECTION
DEGREES
360.0
270.0
180.0
90.0
0.0
183.0
184.0
185.0
DAY
LAT. 46 44.5N, STN 12, CRUISE 80801, INST 5033
LONG. 48 49.5W, STARTING 10:50GMT, DAY 171, 1980
RATE
25 m
CM/S
DIRECTION
DEGREES
183.0
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DAY
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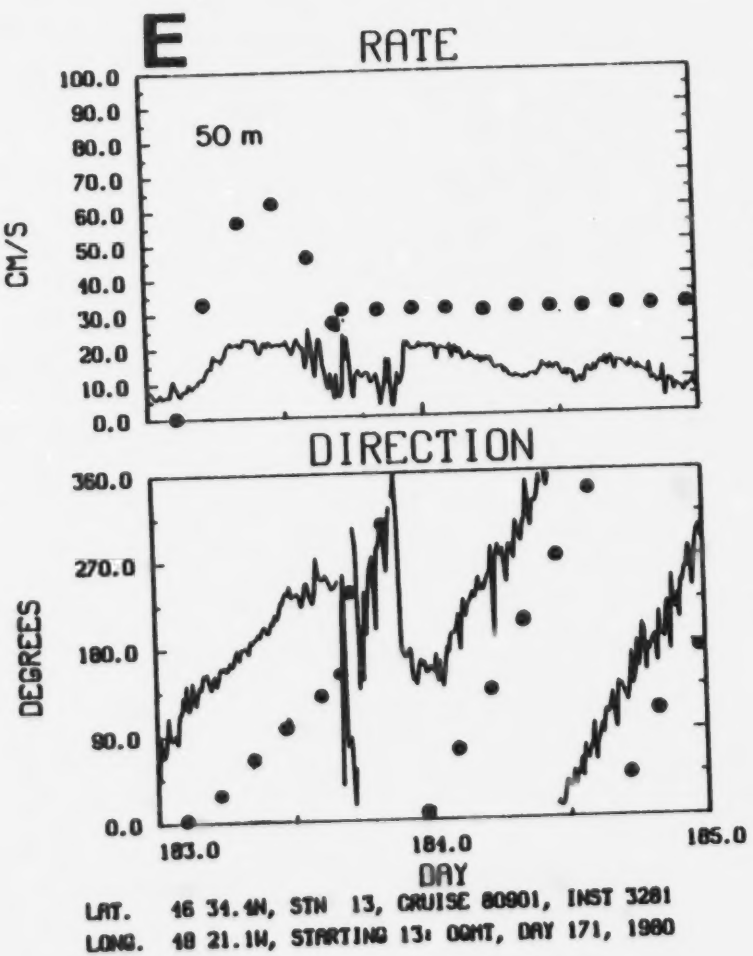

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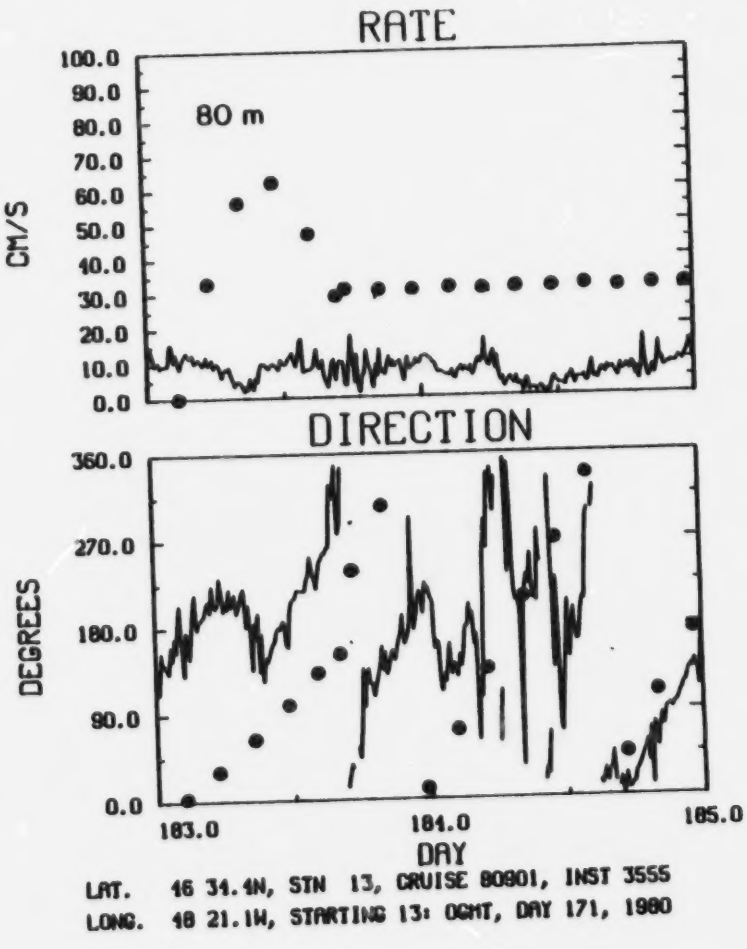

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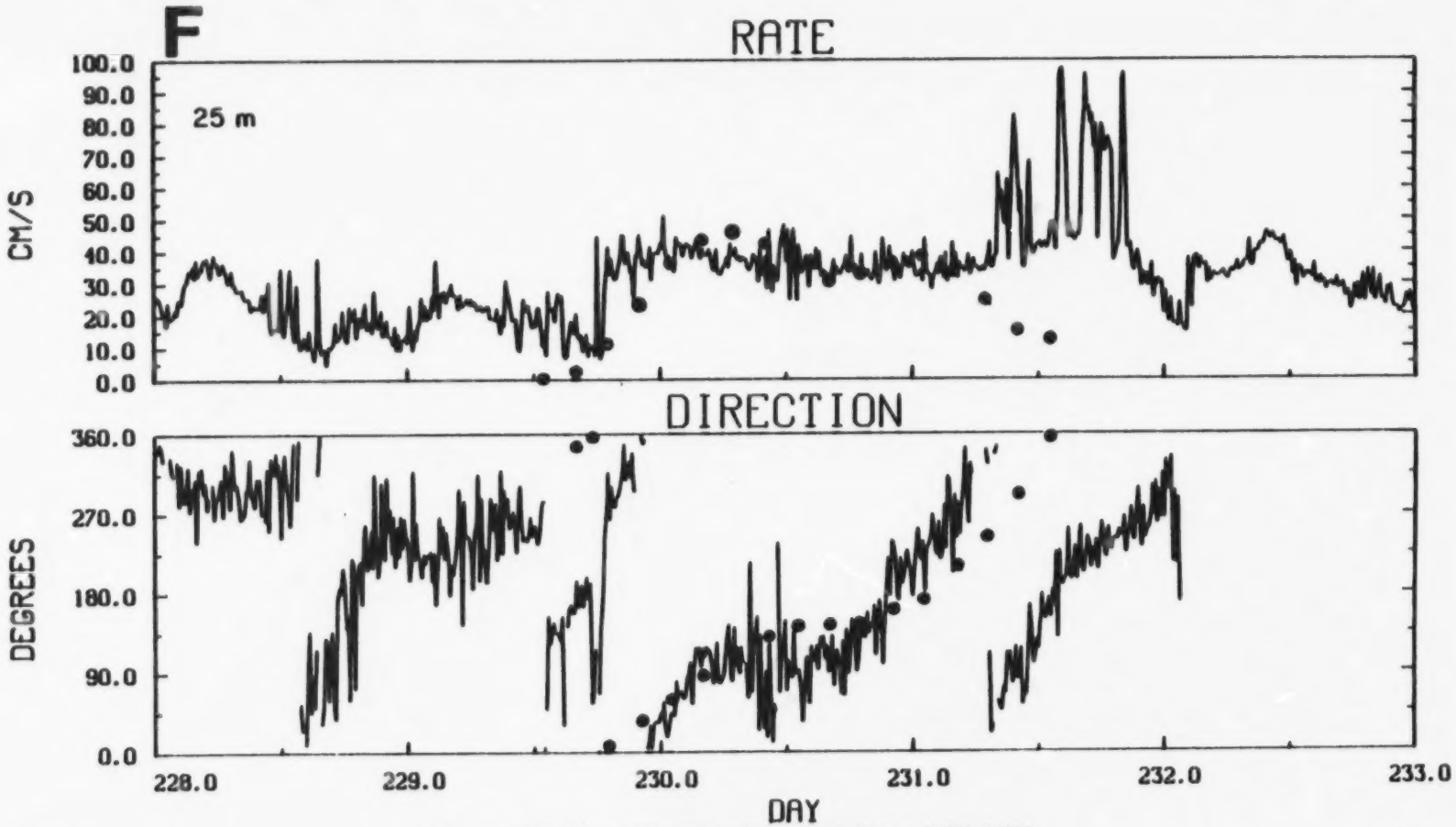

LAT. 46 34.4N, STN 14, CRUISE 80901, INST 2361
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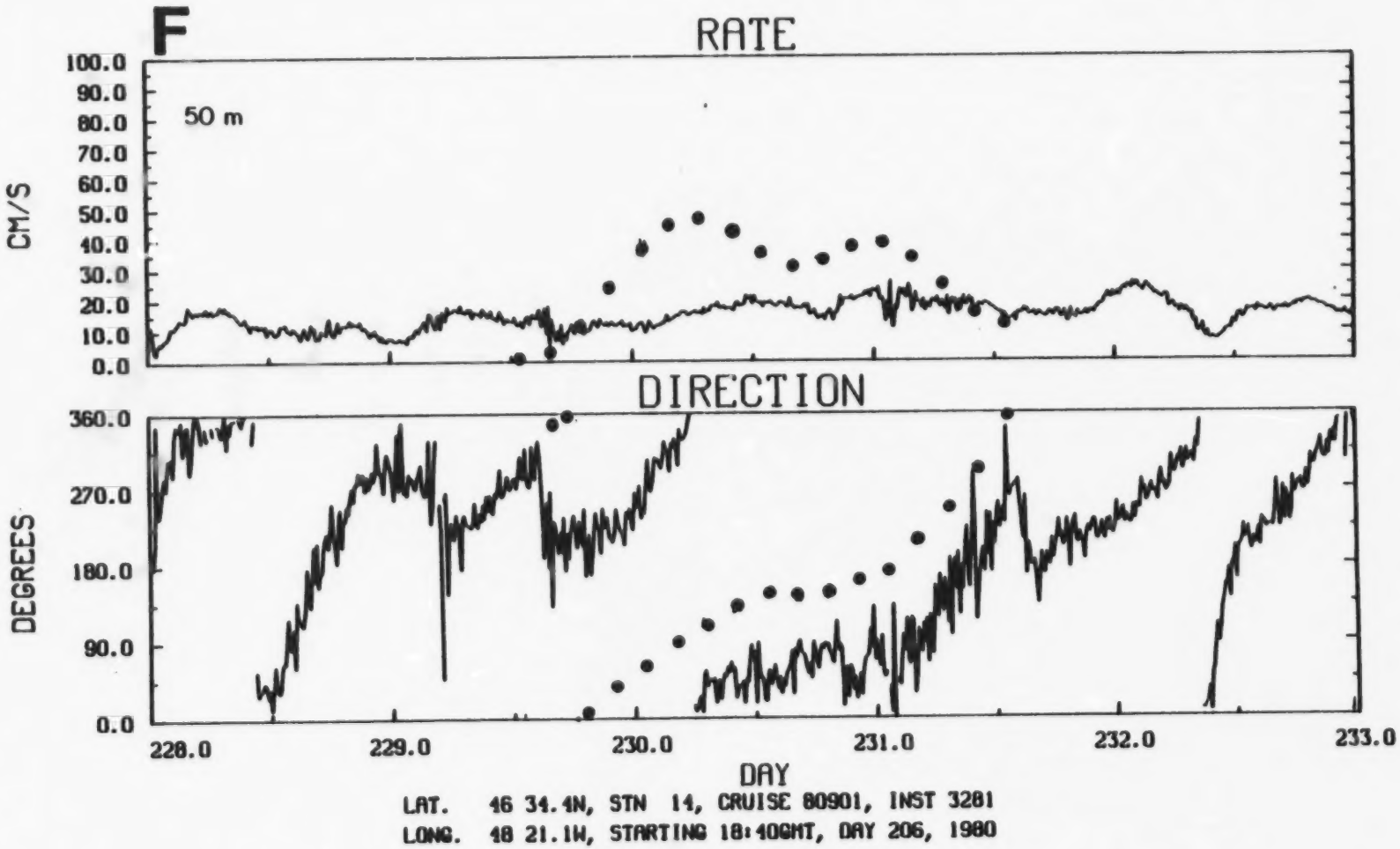
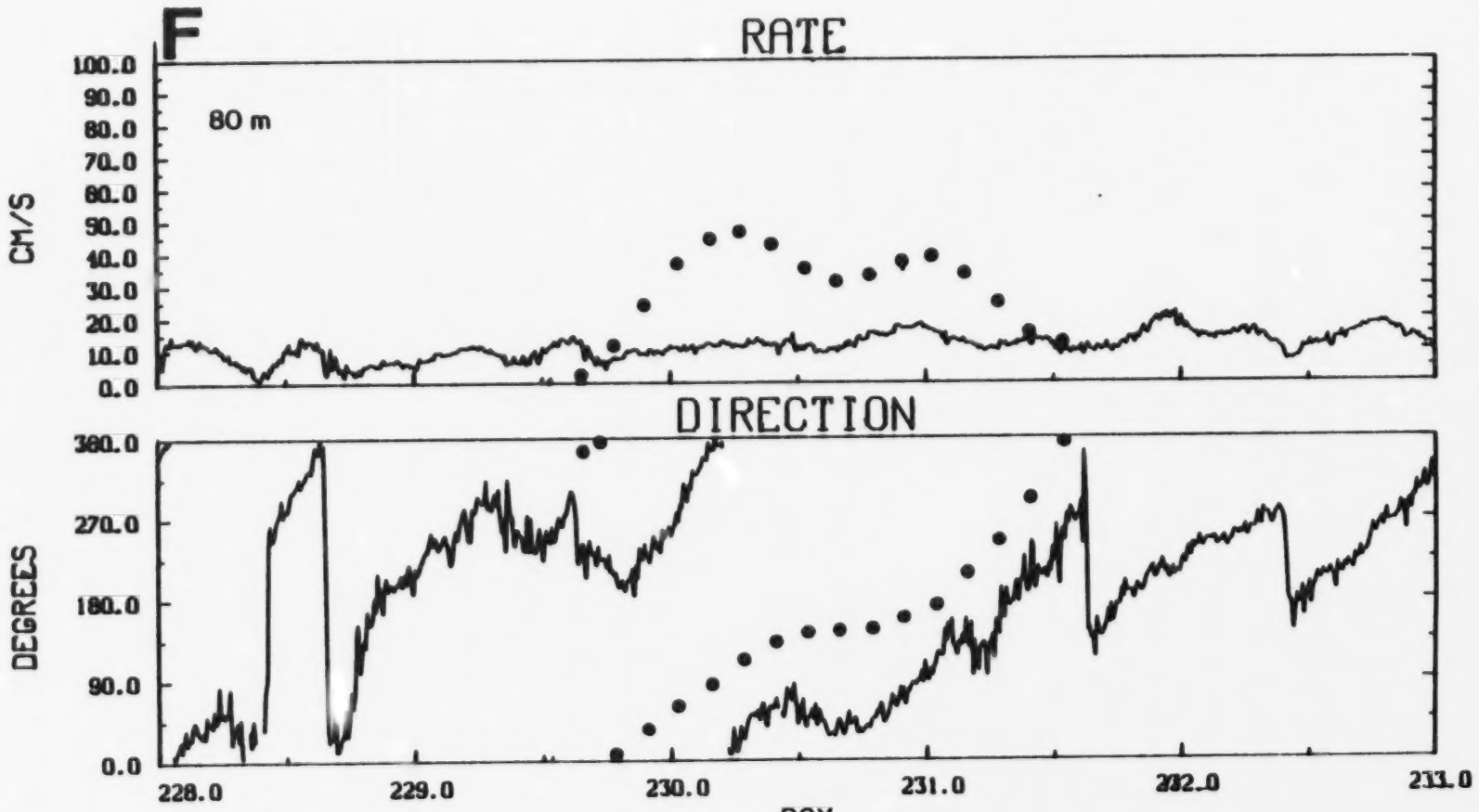

F
RATE
50 m
CM/S
100.0
90.0
80.0
70.0
60.0
50.0
40.0
30.0
20.0
10.0
0.0
DIRECTION
DEGREES
360.0
270.0
180.0
90.0
0.0
228.0
229.0
230.0
231.0
232.0
233.0
DAY
LAT. 46 34.4N, STN 14, CRUISE 80901, INST 3281
LONG. 48 21.1W, STARTING 18:40GMT, DAY 206, 1980



LAT. 46 34.4N, STN 14, CRUISE 80901, NNST 3965
LONG. 48 21.1W, STARTING 18:40GMT, DAY 206, 1980

Event C, Fig. 13(C). Again currents are underestimated and bear little resemblance to the observations. In part, this may be due to poor specification of the input wind, continuous data were not available. Direction, however, agrees reasonably well. Peak significant wave height was 5.3 m.

Event D, Fig. 13(D). Two moorings were in place during this event, one near Sedco 709 and another near Zapatu Ugland. The water column was stratified so the model is really only applicable to observations taken in the surface mixed layer. In spite of this, the deeper observations are shown as well. Allowing one to shift the direction axis could produce excellent agreement for the surface layer but approximatley a 180° discrepancy for the deepest instrument. The record appears to be dominated by inertial period motions. The model overestimates the current speed. Peak significant wave heights were 3.5 m.

Event E, Fig. 13(E). Two moorings were also in place during this event and the water was stratified. It was assumed that when the wind dropped to zero after 14 h at 18 m/s, the "steady" component of flow ceased and only the inertial period motions remained. Peak current is overestimted substantially and occurs about 4 h earlier than peak observed current. Directions appear to be similarly offset. The largest significant wave height was 3 m.

Event F, Fig. 13(F). Perhaps the best agreement between measured and calculated current speed and direction is achieved for this time period. Again the water column is stratified, so agreement may be expected only for the near surface current meter. Current speed is diminished and direction lags for the deeper observations. Peak significant wave height was about 4 m.

A simple one-dimensional model has been used with idealized wind forcing to obtain analytical expressions for the response of the upper layer of the ocean. The model neglects stratification, dissipation, deepening of the mixed layer, topography and pressure gradients. Not only is the model overly simplified but the observations, which could be compared to model results, are degraded due to the presence of energetic wave motions. For cases A-F (Table 9) one has the impression that direction has been modelled better than rate (events C, D direction better, A, B and F about equal, E equally bad). Rate appears to be underestimated when the water column is unstratified (A and C) and overestimated during periods of stratification (D and E). The former may be due to wave action while the latter may be due to deepening of the mixed layer or less momentum transfer between the atmosphere and ocean because of gravitational stability of the air mass over the cooler water. One is left with the feeling that with data uncontaminated by wave action and a less restrictive model better agreement may be possible.

A model based on regressing the wind field on the empirical orthogonal decompositon of currents may be a useful alternative to dynamical modelling. As a first step the modes for current and wind together were calculated. If a significant amount of wind and current variance were coupled then it would be useful to pursue the regression analysis. Unfortunately, there were only 3 sets of current data which could be combined with the wind because of gaps in the latter from March to July. One of these (Feb.-March, 1980) had useful data at only one depth. This leaves one summer data series of 30 d duration and one fall series of 90 d duration (short records had been joined together). Table 10 shows the results

TABLE 10. Empirical Orthogonal Decomposition of current meter observations (filtered to remove tides and high frequency) from joined data taken at Sedco 706 and Ocean Ranger sites (Oct.-Dec., 1980) at 25, 45 and 60 m. Total depth = 75 m.

Mode	Percent Variance		25 m		45 m		60 m		Wind	
			V	U	V	U	V	U	V	U
1	41	Amplitude	-0.19	0.75	-0.24	0.48	-0.09	0.05	0.28	-0.15
		Correlation	-0.27	0.97	-0.39	0.81	-0.22	0.13	0.67	-0.33
2	35	Amplitude	0.69	0.14	0.58	0.28	0.11	0.02	0.02	-0.27
		Correlation	0.95	0.17	0.89	0.43	0.25	0.05	0.04	-0.56

of an analysis on the latter with only the first 2 modes shown (mode 3 had only 7% of the variance). The structure for the current is nearly identical to earlier results (Table 6). The first mode shows the V component of wind and the U components of current at the 25 and 45 meter depths to be significantly coupled. The second mode shows the U wind component coupled to the V current components. In both cases the currents are responding to the wind in the Ekman sense. The first 2 modes account for about 90% of the current variance at 25 and 45 m and about 45% of the wind variance. It may be appropriate to try the same techniques for wind stress as well. Modes 3 to 6 link the variance of the currents at 60 m to that of the wind. Given the 2 years of current and wind data, this approach would be worthwhile to pursue.

9. SUMMARY AND DISCUSSION

This document has attempted to examine some of the non-tidal currents in the vicinity of the Hibernia site. Section 2 presented the distribution of current speed and direction based on the 1980 data. Sections 3 and 4 dealt with seasonal changes in current spectra and variance in three distinct bands. It was apparent that the low frequency (0.5-0.1 cpd) energy increased in fall and winter in accordance with changes in the wind forcing which was dealt with in Section 6. It was also evident that the high frequency (greater than 0.5 cpd) energy increased during the same period implying wave action was affecting the instruments. The vertical structure of low frequency currents was addressed in Section 5, in part, by empirical orthogonal function analysis. It was anticipated at this point that this decomposition might be useful in statistical models of wind

induced currents. Most of the variance in the currents could be accounted for by two modes. Inertial motions were also examined and in general showed greater phase differences between like components of current displaced vertically during spring and summer (stratified water column) than at other times. Section 7 indicated that wave motions probably have seriously degraded the quality of current measurements. Both high and low frequency flows could have been seriously affected. This contributed in part to the unsatisfactory comparison between model results and current observations in Section 8 though not entirely discouraging further efforts.

One of the main purposes of this document was to present estimates of extreme currents for time spans up to 100 years. These estimates could then be used for engineering purposes towards the design of production facilities at the Hibernia site. This was to be achieved by developing a dynamical or statistical model of wind induced currents for the site and then utilize the wind climatology to predict flow extremes. These estimates would be combined with tidal and mean currents to give a final maximum flow. However, the data and/or models were not good enough to achieve this goal. Thus, the main question remains unanswered. However, it may be worthwhile to make some estimates based on simple balances.

First, though, consider the measurements taken in 1980. The maximum residual, maximum tidal and mean currents are given in Table 11. Mean flows were computed the same way speed and direction statistics were calculated in Section 2. Combining these results maximum currents of 1.3, 0.95, 0.90 and 0.45 m/s could have occurred at near surface, mid-depth, near bottom and bottom (1/2 m off bottom) depths.

To estimate wind driven currents based on simple force balances

TABLE 11. Maximum currents (m/s) from 1980 current meter observations.

	Near Surface	Mid-depth	Near Bottom	Bottom
Residual Current	1.0	0.7	0.7	0.3
Tidal Current	0.26	0.21	0.18	0.15
Mean	0.024(185°T)	0.019(201°T)	0.02(171°T)	0.004(214°T)
Maximum	1.3	0.95	0.90	0.45

requires knowledge of the wind field. Swail and Saulesleja (1981, Table 6) indicate that a storm with winds greater than 30 m/s and lasting for 54 hours should occur every 100 years. They do not indicate a preferred wind direction or period for the event. The estimates which follow are based on a storm with winds of 30 m/s lasting for 54 hours. Calculations will be based on a wind stress vector of 3 Pa (equivalent to 30 m/s) rotating with a period equal to 16.5 hours (inertial period, should result in maximum currents), 3 d (the peak in the geostrophic wind spectrum) and infinity (wind steady in one direction). Linearized (λu, where λ^{-1} is the spindown time) and quadratic ($C_D\, u|u|/h$, where C_D is the drag coefficient) frictional terms will be added to the momentum equations. The model is unstratified with a water depth of 75 m.

The results are given in Table 12. The problem now is which one to choose. The results for the inertial frequency storm are equivalent to the "Bretschneider formula" (see Csanady, 1981, and below for example) where wind stress is balanced by bottom stress. Thus

$$\lambda u = C_D\, u|u|/h = \tau/\rho h$$

For 30 m/s winds, τ is equal to about 3 Pa, which gives wind-driven currents of about 1.35 m/s over the entire depth ($C_D = 1.6 \times 10^{-3}$, Sandstrom 1980) or a spin down time of 2.5 d. The "Bretschneider formula" may be a reasonable approximation (but see Forrestal et al., 1977 where at times bottom stress exceeds wind stress) near the coast where Coriolis terms may be neglected but not as relevant for an area such as the Hibernia site. However, we shall use the value of 1.35 m/s since the Bretschneider formula tends to give an upper bound. Adding the tidal and mean flows we

TABLE 12. Maximum wind driven currents (m/s) as a function of friction and storm frequency. Calculations are based on a balance between acceleration, Coriolis force, wind stress and friction. For a wind stress vector (3Pa) rotating at periods of 16.4 hr (local inertial period) and 3d (peak of wind spectrum), the computation has been made with friction given by $-\lambda u$ and λ^{-1} varying between 1d (highly damped) and ∞ (frictionless). For a stress vector fixed in one direction (steady), the friction has been formulated according to the quadratic law.

Storm Period	λ^{-1} = 1 d	2 d	3 d	4 d	10 d	∞
16.4 hr	0.57	1.13	1.69	2.21	4.32	-
3 d	0.40	0.57	0.66	0.72	0.85	0.98
steady	$C_D u\|u\|/h$	$C_D = 1.6 \times 10^{-3}$	Peak 0.65		Steady state	0.38

obtain near surface maximum current of about 1.65 m/s, a mid-depth maximum of 1.6 m/s, a near bottom maximum 1.55 m/s and a bottom maximum of 1.50 m/s.

Consider now the errors one can put on these values. Estimates based on equating wind and bottom stress depend on the value of C_D, the drag coefficient. They also depend on proper computation of the wind stress and it is only recently (Smith, 1980) that a reliable value of the atmospheric drag coefficient is available for wind speeds of up to 22 m/s. The range of values for C_D in the literature is great (Table 13). Since the 1980 data have indicated that currents of 1.3 m/s for the near surface layer are possible, that can be a lower bound. Using the lowest value of C_D in Table 13 gives a wind driven component of 2.16 m/s. Adding 0.26 m/s for the tidal flows results in a maximum current for the near surface layer of 2.4 m/s, decreasing slightly with depth. The mean value (1×10^{-3}) of C_D for the Oregon and African Shelves results in a maximum current of about 2.0 m/s (wind induced + tidal). We can see then that these crude estimates are rather uncertain. Furthermore, there is another difficulty. In Section 7 we pointed out the importance of waves and the effect they might have on current measurements. Given these extreme wind conditions, one would expect significant waves to develop. A 10 m, 12 sec wave would generate an oscillating bottom current of about 1 m/s in 75 m depth of water. The waves and currents will interact in a non-linear fashion with the effect of an apparent increase in C_D (Grant and Madsen, 1979). It is obvious, then, that to dynamically model the wind driven currents at the Hibernia site may not be so straightforward. The problems of parameterizing wind stress and dissipation processes in the water may limit

TABLE 13. Values of C_D in the literature.

Reference	C_D	Location
Forrestal *et al.* (1977)	0.63×10^{-3}	Gulf of Mexico
Kundu (1977)	0.9×10^{-3} 1.02×10^{-3}	Oregon Shelf African Shelf
Weatherly (1975)	1.6×10^{-3}	Florida Strait
Heathershaw (1974)	$1.73(\pm 0.18) \times 10^{-3}$	Irish Sea
Csanady (1981)	2.0×10^{-3} $1.5\text{-}3.0 \times 10^{-3}$	"Standard value" range

the accuracy of a modelling effort. A statistical model may be a reasonable alternative, given, in both cases, sufficient quality data.

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Tidal Currents and Elevations at the Hibernia Site

This document has been prepared for the Resource Management Branch of the Department of Energy, Mines and Resources

by Brian Petrie

Atlantic Oceanographic Laboratory

Bedford Institute of Oceanography

Dartmouth, Nova Scotia

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1.0 INTRODUCTION

Tidal analysis of the 1980 current meter data from the Hibernia site has been completed. In this document, some typical results will be presented and compared to the Plansearch analyses of the same records. A simple model developed for the M2 constituent was completed and will be checked using the current meter and bottom pressure data. Finally, the amplitude of the long period constituent, MF, will be discussed.

2.0 TIDAL ANALYSIS

Current meter records from 1980 were analysed using Bedford Institute's standard harmonic analysis package for the following constituents: Z0, O1, K1, M2, S2, N2, M4, MS4, MF, P1 (inferred from K1), and K2 (inferred from S2). Typical analyses for three successive moorings at the Zapata Ugland site (May-August) are presented in Table 1. Phase lags are given in terms of GMT.

The principal constituent is M2 with a current of about 10 cm/s and a major axis running roughly east-west. Other components such as S2, K1 and O1 have amplitudes of about 5 cm/s and are oriented approximately east-west as well. At the 25, 50 and 80 m depths these four major tidal constituents could combine to give an east-west current of about 26, 21 and 18 cm/s respectively. In the north-south direction the flows would be about 18, 16 and 14 cm/s.

The amplitudes of the tidal currents were compared to the ones derived from the Plansearch analyses and generally agreed to within 1.3 cm/s. There wasn't consistent agreement in phase between the two analyses. In fact, we think that some of the variations in phase shown in

Table 1 for the M2 constituent may have resulted from the assignment of improper start times to the records. We did not have access to original log sheets or original data translations. We received an edited data set. This may account for some of the discrepancies between our analyses and Plansearch's as well. Orientation of the tidal ellipses generally were within 10°. There are two records whose orientation is in doubt (Table 1), namely, the third records from 50 and 80 m. Plansearch's Report gives the orientation of these ellipses as 97 and 91 degrees respectively while we show 123 and 117 degrees. The differences, -26 degrees in both cases, corresponds to the magnetic deviation for the Hibernia area. We suspect that the correction may not have been applied to the copies of these two records we received but do not have a way of checking this.

3.0 M2 TIDAL MODEL

For a tidal constituent whose alongshore length scale is considerably greater than the length of the shelf, the bulk of the water associated with the tide should flow up the continental slope onto the shelf. Then by continuity, the peak amplitude, u, of the M2 tide, for example, is given by

$$u = (2\pi\zeta x/\tau h)$$

where ζ is the tidal amplitude, x is the distance from shore, τ is the tidal period and h is the local water depth. For St. John's, ζ = 0.353 m while positions and depths for Zapata Ugland and Sedco 709 are x = 330 km, h = 96 m, x = 295 km, h = 76 m respectively. This yields estimates of the onshore flow as u = 17 cm/s (Zapata Ugland) and 19 cm/s (Sedco 709). This is sufficient agreement to continue with a more detailed model. Following the work of Munk et al. (1970), a model was developed for a 400 km wide

continental shelf of depth 100 m which then drops off to abyssal depths. For a site 300 km offshore the following results were obtained:

U = 11.6 cm/s θ = 46° (Major)

V = 6.7 cm/s θ = 136° (Minor)

ζ = 14.3 cm θ = 316° (Elevation)

These estimates should apply to the Zapata Ugland site. The major axis would lie along an east-west line if we choose the shelf break to run in a north-south direction. The currents are in reasonable agreement with the results given in Table 1. Shown in Table 2 are the M2 components for all of the current data other than those taken by the (very) near (0.5 m) bottom instruments. Excluding the results with an asterisk (poor data or taken on continental slope) the average onshore amplitude normalized to 100 m depth is 9.5 cm/s compared to 11.6 cm/s from the model. The ratio of major to minor axes is 1.75 compared to 1.73 from the model. The worst discrepancy is for the elevation where the model result of 14.3 cm, 316° differs markedly from the measured tide (Dave DeWolfe, pers. comm) of 21.7 cm, 331° (a second data set gave 21.2 cm, 333°). These bottom pressure measurements (see Plansearch Report 2) give a maximum tidal range (peak to trough) of 1.45 m with non-tidal effects potentially contributing another 0.30 m.

4.0 LONG-PERIOD TIDE

All of the standard analysis which were run extracted the lunar fortnightly constituent MF (period = 13.66 d). This constituent at times showed amplitudes of nearly 12 cm/s, that is, comparable to the M2 component. However, in view of the variations shown in the data of the

amplitude, orientation and phase in time and space (for example, a marked tendency of the amplitude to be higher in winter and fall than in spring and summer), the cause of the motion at 13.66 d may not be astronomical but may be due to the wind field. Mountain (1980) attributed energy in the 8 to 12 d band detected by current meters on the continental slope south of Hibernia to meteorological forcing. Plansearch did not analyse for any constituents with periods longer than diurnal.

5.0 CLOSING REMARKS

It would appear that, in spite of problems with phase, the tidal current amplitudes at the Hibernia site have been resolved to within a few cm/s. At this stage the data seem inadequate to separate internal from surface tides accurately. However, the former do not appear to have significantly large amplitudes.

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TABLE 1

Tidal Analysis for Zapata Ugland site 46°34'N, 48°21'W for three periods and at three depths. Total depth = 96 m

May-June, (June-July), (July-August), 1981 25, 50, 80 m

Const.	MAJOR Amplitude (cm/s)	MAJOR Phase lag (degrees)	MAJOR Direction (true)	MINOR Amplitude (cm/s)	MINOR Phase lag (degrees)	MINOR Sense of Rotation
25 m						
O1	5.4 (4.2)(3.9)	260 (310)(279)	104 (129)(104)	3.2 (3.5)(1.9)	350 (40)(9)	C(C)(C)
K1	5.3 (4.0)(8.1)	19 (354)(45)	91 (68)(71)	3.9 (3.1)(6.7)	109 (84)(135)	C(C)(C)
M2	11.1 (7.7)(9.9)	36 (329)(56)	104 (98)(107)	6.3 (3.7)(5.2)	126 (59)(146)	C(C)(C)
S2	4.6 (5.1)(4.6)	86 (159)(104)	125 (317)(119)	2.0 (1.6)(2.7)	176 (249)(194)	C(C)(C)
N2	2.6 (1.8)(1.2)	39 (266)(95)	97 (100)(24)	1.2 (1.7)(0.1)	129 (356)(185)	C(C)(C)
M4	0.5 (1.0)(0.4)	248 (301)(296)	107 (320)(115)	- (0.8)(0.1)	338 (31)(26)	C(C)(C)
MS4	0.3 (0.7)(0.5)	337 (119)(151)	109 (341)(40)	0.1 (0.3)(0.3)	67 (209)(61)	C(C)(A)
MF	5.3 (3.7)(3.8)	306 (32)(16)	22 (1) (10)	0.5 (1.6)(2.3)	216 (302)(286)	A(A)(A)
50 m						
O1	4.1 (3.5)(3.3)	275 (249)(288)	78 (84)(116)	3.0 (1.9)(2.0)	5 (339)(18)	C(C)(C)
K1	4.5 (3.7)(4.7)	28 (359)(26)	82 (85)(107)	3.6 (3.1)(4.3)	118 (89)(116)	C(C)(C)
M2	9.0 (8.1)(9.3)	53 (352)(67)	101 (90)(123)	4.9 (4.7)(5.3)	143 (82)(157)	C(C)(C)
S2	3.4 (3.1)(3.2)	98 (49)(257)	119 (122)(330)	1.4 (1.4)(2.0)	188 (139)(347)	C(C)(C)
N2	2.4 (1.4)(2.7)	21 (159)(51)	108 (330)(133)	1.2 (0.7)(1.9)	111 (249)(141)	C(C)(C)
M4	0.7 (0.2)(0.4)	263 (240)(296)	105 (13)(110)	0.2 (0.1)(0.2)	353 (150)(26)	C(A)(C)
MS4	0.3 (0.3)(0.3)	6 (74)(344)	76 (315)(333)	0.1 (0.1)(0.1)	276 (164)(74)	A(C)(C)
MF	5.8 (1.3)(1.4)	307 (51)(13)	9 (354)(346)	1.2 (--)(0.3)	37 (321)(293)	C(A)(A)
80 m						
O1	3.4 (2.7)(3.4)	261 (272)(315)	62 (89)(127)	2.7 (2.5)(2.8)	351 (2)(45)	C(C)(C)
K1	3.1 (3.7)(4.1)	25 (348)(22)	69 (67)(85)	2.6 (3.0)(3.2)	115 (78)(112)	C(C)(C)
M2	8.4 (9.0)(8.3)	65 (352)(57)	94 (100)(117)	5.2 (5.6)(4.8)	155 (82)(147)	C(C)(C)
S2	2.6 (2.8)(3.0)	92 (3)(257)	119 (125)(326)	1.4 (1.6)(1.5)	182 (93)(347)	C(C)(C)
N2	1.8 (1.7)(3.4)	67 (344)(52)	104 (82)(128)	0.9 (1.3)(2.5)	157 (74)(142)	C(C)(C)
M4	0.2 (0.5)(0.2)	353 (135)(262)	97 (77)(54)	- (--)(--)	263 (45)(352)	A(A)(C)
MS4	0.3 (0.2)(0.2)	27 (296)(217)	87 (40)(113)	0.2 (0.1)(--)	117 (26)(127)	C(C)(A)
MF	4.5 (2.7)(0.8)	310 (49)(34)	1 (343)(325)	0.5 (0.8)(0.3)	31 (319)(304)	C(A)(A)

TABLE 2

M2 Component Tidal Analysis for (A) Near Surface (B) Mid-Depth (C) Near Bottom

Start	Lat	Long	MJ (cm/s)	MN(cm/s)	Orientation (True)	Total Depth	MJ/MN	Norm. Ampl. (cm/s)
(A)								
29/1/80	46 45	48 49.5	12.0	6.9	88	86	1.74	10.3
13/5/80	46 44.5	48 49.6	15.1	9.1	90	76	1.66	11.5
13/5/80	46 34	48 21	11.1	6.3	104	96	1.76	10.7
19/6/80	46 44.5	48 49.6	12.9	8.1	87	76	1.59	9.8
19/6/80	46 34.4	48 21.2	7.7	3.7	98	96	2.08	7.4
24/7/80	"	"	9.9	5.2	107	96	1.90	9.5
2/10/80	46 47	48 46	13.4	7.9	90	75	1.70	10.1
"	47 7	47 57.5	4.3	1.2	76	163*	3.58	7.0
7/12/80	46 44.3	48 53.2	17.1	8.2	119	75	2.09	12.8
(B)								
29/1/80	46 45	48 49.5	4.1	2.1	99	86*	1.95	3.5
13/5/80	46 44.5	48 49.6	15.1	9.0	87	76	1.68	11.5
13/5/80	46 34	48 21	9.0	4.9	101	96	1.84	8.6
19/6/80	46 44.5	48 49.6	14.1	8.5	85	76	1.66	10.7
19/6/80	46 34.4	48 21.2	8.1	4.7	90	96	1.72	7.8
24/7/80	"	"	9.3	5.3	123	96	1.75	8.9
2/10/80	46 47	48 46	12.1	7.7	77	75	1.57	9.1
"	47 7	47 57.5	5.0	2.0	83	163*	2.50	8.2
7/12/80	46 44.3	48 53.2	16.0	9.4	131	75	1.70	12.0
"	47 7.3	47 57.5	3.9	1.1	320	163*	3.55	6.4
(C)								
13/5/80	46 34	48 21	8.4	5.2	94	96	1.62	8.1
19/6/80	46 44.5	48 49.6	10.0	5.5	84	76	1.82	7.6
19/6/80	46 34.4	48 21.2	9.0	5.6	100	96	1.61	8.6
24/7/80	"	"	8.3	4.8	117	96	1.73	8.0
2/10/80	46 47	48 46	9.5	4.8	87	75	1.98	7.1
"	47 7	47 57.5	4.2	1.8	95	163*	2.33	6.8
7/12/80	46 44.3	48 53.2	11.8	7.7	319	75	1.53	8.9
"	47 7.3	47 57.5	4.3	1.5	335	163*	2.87	7.0

POOR

QUALITY

ORIGINAL